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A

TREATISE

ON

ELECTRICITY,

IN

THEORY AND PRACTICE.

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TRANSLATED FOR THE AUTHOR

BY CHARLES V. WALKER, F.R.S.

IN THREE VOLUMES.

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TO

THE SECOND VOLUME.

It is three years since the First Volume of the *Treatise on Electricity in Theory and Practice* appeared. This long interval, which has elapsed between the publication of these two volumes, is due to the desire, that I have entertained, of not allowing the Second to appear, until after my having succeeded in giving a satisfactory theory of the voltaic pile. I hope to have solved this difficult and contested question, in a manner that will be accepted by all who have turned their attention to it.

I have also to justify myself on another point; it is the necessity in which I am placed of publishing a Supplementary Volume. The very great development, that I have felt it necessary to give to the subjects discussed in this volume, on account of their importance, and of the very great numbers of works of which they have been the object, have rendered it impossible for me to include in it the Applications of Electricity. I have therefore determined to devote to them a supplementary volume, which will enable me to give to them the extension, which they merit.

This change in my original plan has led me to introduce a second change, namely, the addition of a new Part to the Six of which the Treatise should have consisted. This part, which will be the *Sixth*,—the applications becoming the

Seventh,— will have for its object *The Relations of Electricity to Natural Phenomena*, and will be at the head of the supplementary volume. It may be considered as being as it were a kind of application of the electric theories and phenomena, explained in the first two volumes. It will contain the study of the electricity produced by physiological actions both in animals as well as in vegetables, that of atmospheric electricity and of terrestrial magnetism, as well as the meteorological phenomena, that depend upon them.

Undoubtedly the points, that I have been advancing, might have been treated upon in the Chapter, devoted to the Sources of Electricity; but, independently of the impossibility there would have been, had I decided upon this plan, of entering with sufficient development into the natural phenomena, with which they are connected, it is at the same time more rational and more advantageous to devote to them a special part of this Treatise. Indeed the question is not of sources of the same kind as calorific, mechanical, and chemical actions; they are electric manifestations, due to the setting in action directly by nature herself of probably the same forces, but under different forms, as those by means of which the hand of man produces electricity. These are therefore complex phenomena, the study of which is rather an application, as we have said, than a continuation of that of electric sources.

The supplementary volume therefore will contain Two Parts devoted, one to the Relations of Electricity with Natural Phenomena, the other to the applications properly so called, either to the art of healing, or to the chemical or the mechanical arts. It will appear in the course of the year 1856.

Geneva, November, 1855.

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TREATISE ON ELECTRICITY

IN

THEORY AND PRACTICE.

APPENDIX

TO

THE FIFTH AND SIXTH CHAPTERS OF THE THIRD PART.

BEFORE entering upon the Fourth Part of this treatise, which treats of the phenomena, that arise from *the transmission of electricity through different media*, we have some important additions to make to certain of the subjects, that have been discussed in the Third Part. These additions, which have been called for on account of the progress, that has been made in the science during the interval that has elapsed between the publication of the first and second volumes of this treatise, are indispensable for the comprehension of the remainder of the work. They relate, first, to the Laws that regulate the Mutual Action of Electric Currents; secondly, to the Phenomena of Induction; thirdly, to the Action of the Magnet upon all Bodies.

I. *Addition to the Laws that regulate the Mutual Action of Electric Currents.*

Ampère, setting out from the law that regulates the

mutual action of two electric currents, was led, by means of calculation, to connect with the same principle the action of magnets upon each other, and the mutual action of electric currents and magnets. Having realised by experiment certain cases of equilibrium, to which he had been led by mathematical analysis, he succeeded in finding the elementary law of the mutual action of two infinitely small portions of electric currents, and in establishing, with M. Savary, the identity between a magnet and a solenöid, that is to say, an assemblage of closed electric currents, all moving in the same direction, and perpendicular to a common rectilinear or curvilinear axis.

Ampère's theory, however, failed in certain points of direct experimental demonstration. M. Weber succeeded in filling up this gap, demonstrating by certain experiments, which were as accurate as they were delicate, the complete identity between the laws that regulate the mutual action of two solenöids, and those to which the mutual action of two magnets is subject. This important result has been the means of removing all doubts, that might still have remained, as to the accuracy of Ampère's theory, and consequently has given to it a degree of probability, which approaches almost to certainty.

Weber's apparatus is composed of two rings, formed of copper-wires covered with silk, and arranged with perfect regularity. The interior of one of the rings contains a space sufficiently large for the other to move freely within it. When an electric current is sent through the wire of each of the two rings, the fixed one, which is the outer of the two, tends to make the inner and movable one turn with a force that is at its maximum when their two centres coincide and the planes of their currents are perpendicular to each other. The diameter of the two rings is the axis of rotation; it has a vertical direction. The movable ring is supported by two very fine wires, each of which supports only one-half, so as to be in an equal state of tension. These wires, which are connected at their lower ends with the two ends of the wire of the movable ring, serve to transmit the current to it, by means

of the two metal supports to which they are attached at their upper extremities; the arrangement of the conductors is such as to allow also of the wire of the fixed ring being placed in the circuit, without the slightest friction arising to disturb the motion of the movable ring.

The two suspending wires serve also to measure the force with which the two rings act upon each other; seeing that

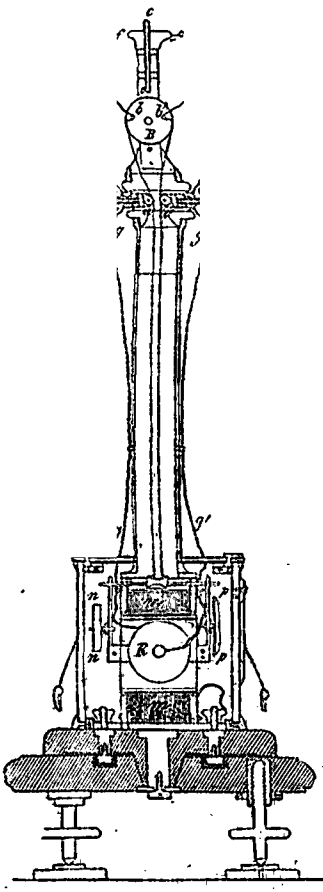

Fig. 170.

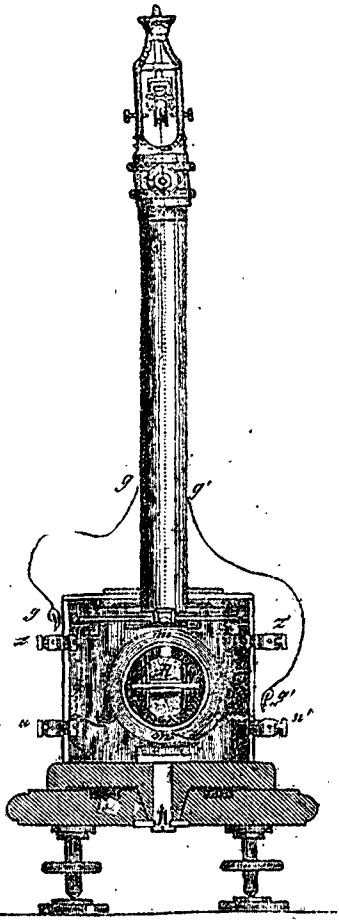

Fig. 171.

every time the movable ring is displaced in a certain angle, a movement of rotation is produced, proportional to the sine of this angle. This is an application of the principle that Gauss employed in the bifilar magnetometer, which we shall describe in the chapters on Terrestrial Magnetism. The movable ring carries a mirror, which serves to measure small angles, by means of a fixed division that is reflected, and then observed by means of a small telescope. *Figs.* 170. and 171. represent two vertical sections of Weber's apparatus, at right angles to each other; and *fig.* 172. a horizontal section of the instrument, seen from above, downwards. The two suspending wires originating at the bobbin R, which they support, rest against two small metal pullies, *a* and *a*, and are secured around two small stems, *b* and *b*, fixed in an ivory pulley, B. This pulley may be lowered or raised, by means of the screw, *e é*, which moves in the nut *f f*, so that the movable ring may be brought into the most convenient position, in respect to the fixed one, in the middle of which it is suspended, and of which *m m'* represents a transverse section. The pulley B, which is movable around a central pivot, is held in equilibrio by means of the mutual action that is exerted at *b* and *b'*, by the two wires that support the movable ring, the weight of which is thus uniformly distributed between the two wires. The mirror *n n*, and its counterpoise *p p*, are erected outside the frame of the fixed ring, which requires, in order to avoid the agitation of the air, that all the apparatus shall be enclosed in a wooden case, provided with two large openings, closed by a plate of glass, so that the movements of the mirror may be followed; its upper part is also of glass, and allows of the passage of a tube, in which the suspending wires are contained, and enables the circular division to be

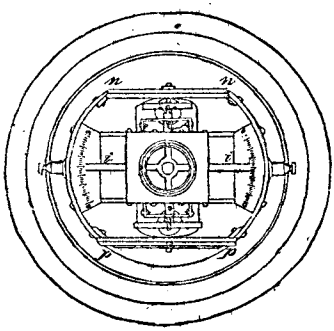

Fig. 172.

seen as well as the index *i i*, that is carried by the movable ring. (Vide *fig.* 172.) The second vertical section (*fig.* 171.), enables us readily to trace the course of the current; the four metal knobs *u u'*, *z* and *z'*, fixed against the wooden case, are used for closing the circuit; *u* and *u'*, are in communication with the two extremities of the wire of the fixed ring, in such a manner that the current setting out from *u*, arrives at *u'*, and after having traversed this wire, it ascends along the wire *g g*, arrives at the screw *e e*, then to the little pulley *a'*, whence it descends along the suspension wire into the movable ring, passes thence to the second suspension wire, from which it reaches the pulley *a*, and thence, by the second screw *c c*, to the wire *g g*, and to the button *z*, which is in communication with the negative pole of the battery. If these conductors are suitably combined, by means of the four knobs, we can easily change the direction of the current in one of the rings alone, on in both.

We should add that the wire of the movable ring is 656 ft. in length, and makes 1200 convolutions; and that of the fixed ring 984 ft. making only 900 convolutions. The two suspension wires, which are very fine, are of silver and have been heated to redness; they are a little over 19½ in. in length from the ring to the pullies *a* and *a'*.

The first law that Weber established by this apparatus, which he calls a *Dynamometer*, is, that *the electro-dynamic force produced by the reciprocal action of two conducting wires, which are transmitting currents of equal intensity, is proportional to the square of their intensity.* The following are the experiments that lead to this law. Three currents of different intensities, produced successively by 3, 2, and 1 pair of Grove's, are passed through the two wires of the dynamometer (*Fig.* 170.); and simultaneous observations are made of the deviations of the dynamometer and those of a galvanometer placed at the same time in the circuit. After having worked out the necessary reductions, the following are the mean values of the inductions of the two instruments: —

No. of Pairs.	Indications	
	of the Dynamometer.	of the Galvanometer.
3	440·038	108·426
2	198·255	72·398
1	50·915	36·932

These observations have been reduced, so that the first gives a measure of the electro-dynamic force, with which the two conductors of the dynamometer act upon each other when currents of the same intensity are made to pass through them, whilst the second gives a measure of this intensity itself. If P represents the dynamo-metric indications, and p, the galvano-metric indications, we have $p = 5{\cdot}19534\ \sqrt{P}$; if we actually calculate from this formula the value of p, by means of those obtained from P, we obtain:

$$p = 108{\cdot}144$$
$$72{\cdot}589$$
$$36{\cdot}786;$$

numbers which, in respect of the value of p, are as near to those furnished by experiment as is possible within the limits of the accuracy that can be given to experiment. So that the law given above is properly the result of the interpretation of experimental data.

The second law established in a direct manner by Weber, and which had only been indirectly established by Ampère, is that *electro-dynamic actions are governed, in respect to distance, by the same laws as magnetic actions.* In order to arrive at this law, we must have the means of varying the distance of the movable ring, in respect to the fixed ring; the movable ring is, in this case, exterior, and the respective distances of the two rings is measured by the distance of their two centres; and it is necessary also to measure the angle formed by the right line passing through the two centres with the axis of the movable ring; these two lines are always in the same horizontal plane. Four directions have been chosen, corresponding with the four cardinal

points; which signifies that if the axis of the movable ring is supposed to be adjusted according to the magnetic meridian, as the axis of a magnetic needle would be, the centre of the fixed ring is found to be deflected, in regard to that of the movable ring, sometimes in the direction of the magnetic meridian, either from south to north, or from north to south; sometimes in a direction perpendicular to this meridian, from west to east, or from east to west. In each of these four directions, the two rings, or rather their two centres, are arranged at different distances from each other. Care was taken that the same current that passed through the dynamometer was also transmitted through the galvanometer, in order that the observations made with the former instrument might be reduced to the same intensity of current, by making use of the first law already demonstrated. The following is a Table, presenting an abridged summary of means, reduced to the same intensity, that had been obtained in the different cases observed. The first column contains the numbers expressing the distances between the centres of the two rings, and the others have at their head the indication of the angle formed by the right line which joins the two centres with the axis of the movable ring set in the direction of the magnetic meridian.

Distances in Inches.	North, 0°.	East, 90°.	South, 180°.	West, 270°.
0	22960	22960	22960	22960
11·29	77·14	189·24	77·06	190·62
15·72	34·78	77·61	34·77	77·28
19·65	18·17	39·37	18·30	39·16
23·58	- -	22·53	- -	22·38

It is evident that in the case where the distance is 0, namely, when the centres of the two rings coincide, there can be no difference arising from the angle made with the axis of the movable ring by the line that joins the centres of the two rings, since this line is reduced to a point situated on the axis.

This table shows us also that the results obtained for the

same distance, but in directions diametrically opposed, sufficiently agree with each other to authorise our finding in this agreement a guarantee of accuracy in the observations. By supposing these values equal, two and two, and taking their mean, we obtain the following table, in which the divisions of the arbitrary scale are transformed into degrees, minutes, and seconds, R being the distance, V and V′ being respectively the angles of deviation.

R	V	V′
0·3	0° 49′ 22″	0° 20′ 3″
0·4	0° 20′ 8″	0° 9′ 2″
0·5	0° 10′ 12″	0° 4′ 44″
0·6	0° 5′ 50″	

According to the fundamental principle of electro-dynamics, the tangents of the angles of deviation should be developed, according to the inverse powers of the distance, which gives:

$$\text{tang. } V = a\, R^{-3} + b\, R^{-5}$$
$$\text{tang. } V' = \tfrac{1}{2} a\, R^{-3} + c\, R^{-5}.$$

In these formulæ *a*, *b*, and *c*, are the constants, that must be supplied by observation; if in the case before us, we suppose:

$$\text{tang. } V = 0{\cdot}0003572\, R^{-3} + 0{\cdot}000002755\, R^{-5}$$
$$\text{tang. } V' = 0{\cdot}0001786\, R^{-3} + 0{\cdot}000001886\, R^{-5};$$

we obtain the following table of *calculated* deviations, which differs but very slightly from the *observed* deviations, as may be seen by the third and fifth columns, which give these differences.

R	V	Difference.	V′	Difference.
0·3	0° 49′ 22″	+ 0″	0° 20′ 4″	− 1″
0·4	0° 20′ 7″	+ 1″	0° 8′ 58″	+ 4″
0·5	0° 10′ 8″	+ 4″	0° 4′ 42″	+ 2″
0·6	0° 5′ 49″	+ 1″		

The method employed, which is exactly the same as that adopted by Gauss for measuring magnetic force (*Institutiones Magneticæ, Annalen* 1833, t. xxviii. p. 604.), leading to the same results, enables us to establish in a direct manner one of the most general and most important consequences of the principle of electro-dynamics; namely, that the same laws regulate electro-dynamic and magnetic actions, at a distance.

In comparing electro-dynamic with magnetic actions, it has been needful to exclude from the former the cases in which the centres of the two rings of the dynamometer coincide with each other, because this case cannot be realised in the mutual action of two magnets. We may further add that in this application of magnetic laws to electro-dynamics, instead of deducing the values of the three constants *a*, *b*, and *c*, from the observations themselves, we may obtain them directly by calculation, by means of the fundamental principle of electro-dynamics; for, by means of this principle, we may find, with a sufficient degree of approximation, *the momentum of electro-dynamic rotation, which the fixed ring exerts upon the movable ring, suspended by the two wires, when a current of an intensity* i, *is sent through the two rings.* We shall not produce here the series of calculations, by which Mr. Weber succeeded in obtaining numerical results almost identical with those, that had been furnished to him by direct observation in the first Table that we have given above, in establishing the second law. We shall content ourselves with giving this Table calculated, and with the differences that it presents, in relation to the corresponding results obtained by experiment.

Distances in Inches.	North or South, 0° or 180°.	Differences.	East or West, 90° or 270°.	Differences.
0	+22680·00	+280·00	+22680·00	+280·00
11·29	189·03	+ 0·90	77·17	— 0·06
15·72	77·79	— 0·34	34·74	+ 0·03
19·65	39·37	— 0·10	18·31	— 0·07
23·58	22·64	— 0·18		

In this comparison between theory and experiment, one factor alone was deduced from observations; and this because, on account of its nature, we could not obtain this factor in a sufficiently exact manner by direct measures.

In conclusion, we believe, we have said enough to explain the immense service M. Weber has done to science, by establishing on such solid bases the laws of electro-dynamics, and by thus giving to Ampère's theory an almost mathematical certainty.

II. *Additions to the Phenomena of Induction.*

We have seen (Vol. I. p. 363.) that, after having discovered inductive currents, Faraday was not long in showing that the existence of these currents might give a very satisfactory explanation of Arago's magnetism of rotation. He had even made a very ingenious analysis of the manner in which the indirect currents must be established and circulated in the metal disc. MM. Nobili and Antinori had succeeded in collecting those currents; but their processes and results were not entirely free from objection. M. Matteucci has lately taken up this particular point, which is of very great interest in respect to the theory of rotation; and, while he confirms the views that were entertained by Faraday, he has succeeded in making a detailed and accurate experimental analysis of the complicated phenomena in question.

Matteucci's method consists in causing a very smooth copper disc to rotate in a vertical plane, under the influence of the two poles of an electro-magnet, the horizontal branches of which reach very near to the disc without touching it, and at equal distances from its centre. N and S (*fig.* 173.), are these two poles. After having demonstrated that the disc is maintained by induction, in the same electric state as a metal plate would have if in communication with the two poles of a battery, M. Matteucci found in it, as in the plate, lines of *no current*, which are indicated on the figure by the numbers 1, 2, 3, 4, and 5. These lines of no current bend near the edges of the plate, so as always to cut them normally.

It is always a very easy matter to find them, by keeping one of the terminations of the galvanometer fixed, and moving

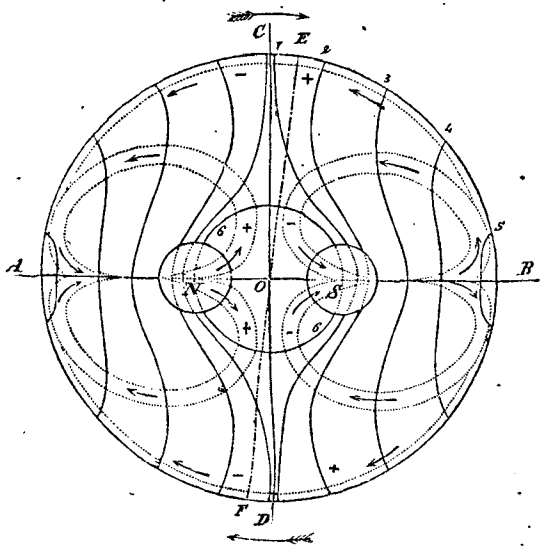

Fig. 173.

the other ever so little; for on the right, or on the left of the line, the currents obtained are in the contrary direction. With regard to the electric currents, that is, the filaments of maximum intensity, they always cut the lines of *no current* normally; they are represented on the figure by the closed and dotted curves. The direction of these currents can only be determined, when we have previously discovered the lines of no current.

Besides the lines of no current already indicated, there is one, marked in the figures with the number 6, which is circular, and which separates the opposite electric states. M. Matteucci calls it the neutral and the *inversion* line; it is analogous to the right line, which, in the case of a plate traversed by an electric current, cuts through the middle of the line that connects the poles of the battery. It is the existence of this neutral or inversion line, which necessarily compels us to admit the existence of four systems of currents,

that is, two and two symmetrically on the side of each pole. It is through not having known this line, that the philosophers, whom we have just mentioned, had not been able to analyse the effect of the magnetism of rotation in Arago's disc. The dotted line F, F, is also a neutral line; but it is displaced by rotation, and in proportion to the rotation. Around this line all is symmetrical, and all consequently is displaced with it.

Thus, induction determines in the disc, rotating in presence of a magnet, a state of dynamic equilibrium, which may be considered as fixed in space, and which is represented by *neutral* lines, and by lines of *no current*, that are cut normally by filaments or electric currents. In proportion as the velocity of the rotation of the disc increases, it is found that these lines and the system of induced currents, is displaced in the direction of the motion, and proportionately to the velocity of rotation.

M. Matteucci, in order to show the accuracy of his analysis, succeeded in verifying, by means of electric currents, distributed artificially, as he admits they are, by the effect of induction in the copper disc, all the effects of compound differences found by M. Arago. For this purpose, he arranges a silk-covered copper wire upon a plane of wax, so as to have circuits resembling those of the rotating disc, and he sends an electric current through these circuits, taking care to place the bar-magnet in the proper position. In order to complete the resemblance, we have merely to take into account the displacement of the circuits due to rotation, in the case of the disc.

We can now easily comprehend the influence that is exercised, in the phenomena of magnetism by rotation, by solutions of continuity in the disc; if they diminish the action in proportion as they are more numerous, it is because they oppose the circulation of the induction currents, by thus modifying their numbers and direction; in fact, we have merely to fill up the slits of the disc with a conducting metal, in order to re-establish the interrupted circuits, and thus to restore to the action almost the entire of its primitive energy.

With induction, also, is connected Weber's phenomenon, known by the name of *unipolar induction*, and of which we have endeavoured to give an explanation, contrary to the first ideas of Weber and of Faraday, on this particular point. Our explanation is found to enter implicitly into the more general laws due to Lenz, and which we think it useful to repeat in this place, adding to them some researches of Faraday's of the same nature, and a theory of these phenomena, that has been suggested to us by the labours of Lenz and Faraday.

A short time after Faraday's discovery of electro-dynamic induction, Lenz succeeded in reducing the results into formulæ, in a very simple and very satisfactory manner. The following is the principle that he established:—*If a metal conductor is in the vicinity of an electric current, or of a magnet, an electric current is developed in it, the direction of which is the same as would have been produced in this wire by a motion directly contrary to that which had been given to it in order to develope the induction current, supposing that the wire could only be put in motion in the same direction in which it had been moved, or in a precisely opposite direction.* It follows from this principle that it is always an easy matter to know in what direction the induction current ought to travel, bearing in mind that the direction is the inverse of that in which a current would travel that would produce by electro-dynamic action the same motion that is imparted mechanically in order to develope the induction. Lenz thus connects in an intimate manner the phenomena of induction with Ampère's electro-dynamic phenomena; for to each phenomenon of electro-dynamic motion corresponds a magneto-electric phenomenon, or one of electro-dynamic induction. This may be easily demonstrated by examining different cases successively.

1st. Case of two parallel conducting wires, each traversed by currents, which attract or repel each other according as they pass in the same or contrary directions. Corresponding case of two parallel conducting wires, of which one alone is traversed by a current, while the other is mechanically

made to approach or to recede, which determines in it a current in the contrary direction or in the same direction.

2nd. Case of two conducting wires bent into rectilinear forms, or into circles of the same size, and capable of moving around the same axis in vertical planes, and arranged first so that their two planes are perpendicular to each other; they move and place themselves one against the other, when they form part of an electric circuit, in such a manner that the currents have the same direction in both. Corresponding case of two similar conductors, the one fixed and traversed by a current, the other movable, in which a current is developed moving in a contrary direction to that of the fixed one when it is applied mechanically against it.

3rd. The case of a movable and limited rectilinear conductor, capable of being moved parallel to itself, along an indefinite rectilinear conductor; when both are traversed by a current, the movable one moves along the fixed one in the direction of the current of the latter, if its own current is receding, and in the contrary direction if it is approaching. Corresponding case of an indefinite and fixed conductor, traversed by a current, along which a movable and limited conductor is made mechanically to pass; a current is developed in it directed towards the indefinite conductor, when it travels in the direction of the current of this conductor, and a current directed in the reverse way when it travels in a direction opposite to that of the current of the indefinite conductor.

4th. Case of a magnet directed from south to north, and a conductor parallel to the axis of the magnet, to which an angular motion is given, sometimes to the east, sometimes to the west; there is developed in it an inductive current, moving in a contrary direction to that which should traverse the conductor, in order that the latter might give to the magnet a deviation in the same direction as that which is mechanically given to it.

5th. Case of a ring or helix, formed of wire, which is made to move to the middle of a magnet, that forms its axis, there is developed in it a current, moving in the in-

verse direction to that which should traverse the wire of the ring in order that the latter might be attracted to the middle of the magnet if the pole of this magnet should be presented to the centre of the movable ring.

6th. Case of a metal disc, moving in a circular direction in a horizontal plane between the poles of a horse-shoe magnet, one of which is above and the other below it; there is developed in it a current, moving from the centre to the circumference, when the disc travels in the direction of the hands of a watch, and the north pole of the magnet is above and the south below; the current has the reverse direction if the disc travels in the opposite direction, or the poles of the magnet are reversed. This experiment corresponds in electro-dynamics with Barlow's experiment, in which a wheel traversed by an electric current, moving from its centre to its circumference, turns between the poles of a magnet (*fig.* 115. p. 264. Vol. I.). The induced current has an opposite direction to that which the current should have, that would give to a wheel a motion occurring in the same direction as that which is impressed upon it mechanically.

7th. Case of a magnet, turning on its axis under the action of a current moving from the middle to one of its extremities, or from one of its extremities to the middle; the magnet moves by the effect of the currents in the mercury into which it is plunged, or of the fixed conductors, by which it is placed in the electric circuit (*figs.* 104. and 105. p. 250. Vol. I.). Corresponding case of a magnet, one of the poles of which and the medium are put into communication with the ends of a galvanometer. On imparting to the magnet a motion of rotation upon its axis, a current is obtained in the galvanometer moving in a direction contrary to that which, if it traversed conductors arranged in respect to the magnet as the ends of the wire of the galvanometer are, would impart to the magnet a motion on its axis, having the same direction as that, which had been imparted to it mechanically.

As may be seen, the phenomenon of unipolar induction enters into the seventh case, and consequently into Lenz's law.

This law, moreover, has this remarkable feature, that it establishes the link between the nature of electro-dynamic motion and that of the corresponding induced current. Indeed, whenever the mutual action of two currents, or of a current and a magnet, gives rise to a limited motion, such as an attraction or a repulsion, or a deviation in one direction or another, the corresponding inducing action determines an instantaneous current; whilst, when the electro-dynamic action produces a continuous motion, such as a rotation, the corresponding inducing action developes a continuous current. Thus, the induced currents of the cases 1, 2, 4, and 5, are instantaneous, either in one direction or the other; whilst the currents of the cases 3, 6, and 7, are continuous, and in the direction conformable to the law.

Still more recently, Faraday, with a view of studying the magnetic field, namely, the distribution of the forces that emanate exteriorly from the poles of a magnet, by making conductors rotate under the influence of a magnet or of terrestrial magnetism, obtained induction effects, that are a remarkable confirmation of Lenz's law. We shall return to these experiments further on, when we are speaking of Faraday's lines of magnetic force; for the present we shall confine ourselves to the particular point of induction. It is obtained in the following manner in this case. Two magnets are arranged one beside the other with their homologous poles situated towards the same extremity, so that they may act like a single magnet, and turn around a common axis. A wire, coming from one of the polar ends, follows the direction of the axis, to the middle of the magnetic system (that is the *axial* part), and thence taking a direction perpendicular to the axis (this is the *radial* part), returns to its starting point, by describing a curved line of greater or less extent, which is completely exterior to the magnets. These different parts of the wire may have independent motions, but they communicate metallicly together by means of copper rings, to which the ends of the axial part are attached, and against which the extremities of the radial parts press. Motion may be imparted to the magnets around their

common axis; and in this case, the inducing wire remains fixed; instead of imparting motion to this wire, it is the magnets that are moveable. When the radial part and the exterior part, namely, all the part of the conducting wire comprised between the two points where it reaches the axis, are set in motion in the same direction, there is not the least trace of a current, which is due to there being two equal and contrary currents developed, one in the radial part, the other in the exterior part; this is easily proved by moving each of the parts separately. When the axial part of the wire is alone set in motion, there is no effect; this portion then acts only as a conductor, a duty which might equally be discharged by the substance of the magnet itself. The nullity of effect, that we have been pointing out, is in strict accordance with one of the consequences of the laws of electro-dynamics, laid down by Ampère in one of his later memoirs; namely, that the action of a magnet on a closed current which enters its axis by its two extremities, is perfectly null; and this, whatever be the form or extent of the curve that the current describes, and whatever be the points of the axis at which the extremities of the wire that conducts the current, enter. Now, this is exactly the case in Faraday's experiment.

This very remarkable correspondence between the phenomena of electro-dynamics and those of magneto-electric induction, and which presents itself in each individual fact, has naturally led philosophers to endeavour to comprehend them under one theory; we have already succinctly described the labours of Weber and those of Newmann on this subject; but it appeared to me that, without going into notions and calculations so deep as those of Weber and Newmann, we may consider induction as the result of decomposition by influence of the natural electricity of each particle of the induced conductor, by the electricities, that are already separated, of each corresponding particle of the inducing wire. For this purpose we must admit, that the propagation of the current is made by a series of decompositions and recompositions of the electricities of the successive molecules, in the same manner

as in the case of insulated bodies, as we have seen in the Fifth Chapter of the Second Part.* We shall give in the Fourth Part the numerous proofs that operate in favour of this mode of the propagation of the electric current.

Let, therefore A B (*fig.* 174.), be a conductor, traversed by

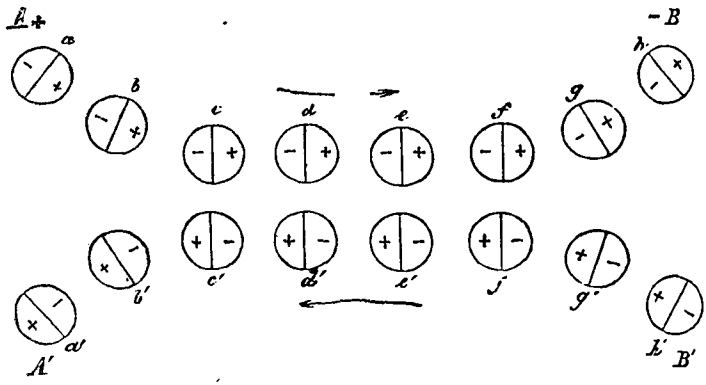

Fig. 174.

a current in the direction from A to B; the successive particles, of which it is constituted, have their natural electricity decomposed, the — turned to the side A, where the positive pole of the apparatus is — the + turned towards B, where the negative pole is. The electricities, as soon as they are separated, combine from particle to particle; namely, the negative of *a* with the positive of the pole A, the negative of *b*, with the positive of *a*, and so on to the positive of *h*, which combines with the negative of the pole B. This recomposition which is instantaneous, is immediately followed by a new decomposition; and this by a recomposition, and so on. This succession of decompositions and recompositions is so rapid, that there is always, as we discover by experiment, an electric tension in each particle of the conductor; so that we may consider that the state in which it is represented in *fig.* 174., which we call a *state of polarisation*, is very nearly permanent.

Let there now be a second conductor A' B' (*fig.* 174.), si-

* *Vide* Vol. I. p. 139.

milar to the first, as near to it as possible, but insulated from it by silk or wax; at the moment when the current is sent along A B, and when consequently its particles are polarised, an opposite molecular polarisation is produced in A′ B′, the + of each particle being opposite to the — of each particle of A B; and the — opposite to the +. It follows, that if, at the moment when A B is traversed by a current, the extremities of A′ B′, are connected by a conductor, as, for instance, the wire of a galvanometer, the + of the molecule a', combines, through this conductor with the — of the molecule h', and thus produces an instantaneous current, directed from A′ to B′ in the conductor, but from B′ to A′ in the wire A′ B′ itself; namely, in a contrary direction to the inducing current. In like manner if, instead of being connected by a conductor, the extremities A′ and B′, are in communication with the two plates of a condenser, A′ gives to it a change of positive electricity, and B′ one of negative. As soon as a' has lost its positive, and h' its negative electricity, the negative of h', is disguised by the positive of b', and so on, to the negative of g', which is disguised by the positive of h', these electricities neutralise each other, because they are retained by the opposite electricities of the particles of A B; but, at the moment when the current ceases to pass along A B, then if the two extremities of A′ B′ are united by a conductor, the negative electricity of a, unites with the positive of h, and at the same time, the contrary extremities of each of the particles a', b', c', d', e', f', and g', combine and produce a current moving in the direction from B′ to A′, and from A′ to B′, in the wire A′ B′ itself. Thus A′ B′ is in this case traversed by a current, moving in the same direction as the inducing current. The state of electric tension, in which the wire A′ B′ is found, while the current is traversing the wire A B, is what Faraday called the *electro-tonic* state; and the cessation of this state produces the second inductive current, whilst its creation, produced the first. We may conceive from the preceding theory, that the electric tension of the extreme molecules will be stronger, in proportion as the induced wire is longer; for if it is short, the two electricities accumulated at

its two extremities, will unite more easily through the wire itself*; on the other hand, in order to produce a strong current, it is necessary to have a good conductor, so that the decomposition of the natural electricities of each of its particles and their recomposition may be brought about more easily. Finally, in the theory that we have just given, the production of the two instantaneous inductive currents, is similar to what takes place in the charge and discharge by cascade of consecutive Leyden jars, the interior coating of each of them being in communication with the exterior of the preceding.

It is well known that, instead of developing the induced current by sending a current along the inducing wire, we may produce it by mechanically moving A B, which is traversed by the current to or from A′ B′, which is not; we thus obtain an induced current, which is stronger in proportion as the mechanical motion is brought about more rapidly; but, however, never so strong as in the former case, all other circumstances being the same. It is true that the current has in this latter instance a little longer duration. In this case, the molecules of A′B′ do not, as in the case of the invasion of A B by the current, suddenly experience the influence of the molecules *a*, *b*, and *c*; thus instead of a single and instantaneous current, we obtain a series of little instantaneous currents, the intensity of which increases in proportion as the approximation goes on, and the sum of which constitutes a temporary current.

When, instead of producing the induction by the electric current, we obtain it by means of a magnet, the theory is exactly the same providing we bear in mind that a magnet may be compared to a series of currents all moving in the same direction, and perpendicularly to the axis of the magnet; only the action of the currents of the magnet is much more energetic than that of true electric currents, which is probably due to their greater number.

It remains for us to examine the case, in which the in-

* MM. Guillemin and Burnouf have even succeeded in obtaining electrodynamic induction in a long telegraphic wire, insulated at one of its extremities.

ducing and induced wires, having a continuous movement in respect to each other, the inductive current is also found to be continuous; the same theory fully explains the effects. Suppose the conductor AB (*fig.* 175.), traversed by a current

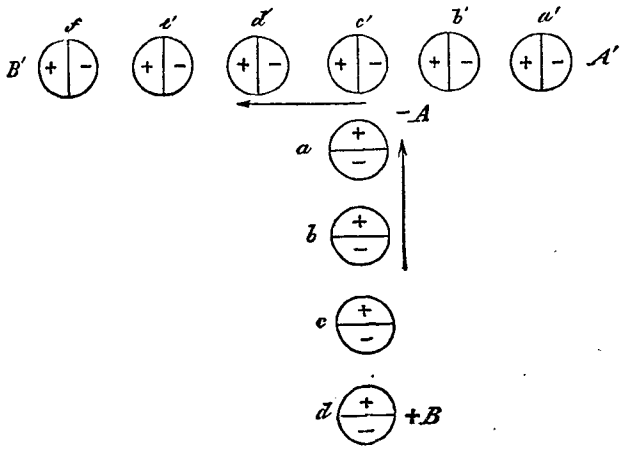

Fig. 175.

from B to A, to be moving along the indefinite conductor A'B'; the + of the molecule *a* of AB, travelling from A' to B' decomposes the natural electricity of each of the particles *a' b' c' d'* &c., before which it passes; it attracts the −, and repels the +, which immediately gives rise to a current directed towards B', and going from B' to A' in a conductor, connecting the two extremities of A'B'; this current is reproduced every time that *a* passes before a molecule in A'B', and consequently so long as the motion of AB continues before A'B'. The direction of this current entirely corresponds with what it should be according to Lenz's law; for it is the reverse of that which would give to AB a motion having the same direction as that of the mechanical motion that is imparted to it; but its intensity is very feeble, which is due to there being only the extreme particles

of AB, namely, those which are nearest to A′B′, that can act upon it.*

With regard to the current induced in the inducing wire itself, which occurs at the moment when the current ceases to pass, it is simply the effect of the return of the molecules to their ordinary state, when the molecular polarisation has ceased. For instance, let us suppose that, in the wire AB of *fig.* 175., we suspend the passage of the current, and at the same time connect A and B by a conductor, the positive electricity of *h* is united through this conductor, with the negative electricity of *a*, the positive of *a* with the negative of *b*, and so on; we shall then have a current directed from B to A in the conductor, and from A to B in the wire itself; and consequently, in the same direction as that which had been traversing it, but it will be merely instantaneous. It is easy to understand why, when we collect the extra-current, the current induced in the wire A′B′ almost entirely ceases; this is because the direction in which the electricities of the molecules of AB were travelling draws those of A′B′ in a contrary direction to that which would have given rise to the induced current.

The numerous experiments of M. Masson, relative to the induction of a current upon itself, are altogether favourable to the explanation I have been giving of the extra-current.†

* M. Wartmann had even believed that there was no production of inductive current, in the case in which the induced wire was perpendicular to the inducing wire; his error arises from the circumstance of the current being very feeble, and, perhaps, also from M. Wartmann's having operated with conductors that crossed each other, whilst it is necessary that one of the wires should be entirely on the same side as the other, as in *fig.* 175.

† The helical form given to the conductor favours, in a very decided manner, as far as equal lengths are concerned, the production of the extra-current. And for this reason; that in addition to the cause that we have just assigned to this production, and which acts alone in the case of a rectilinear conductor, we have here added the inductive action of each spiral of the helix upon the neighbouring spirals, the effect of which must be added to that of the general cause, since it is exercised in the same direction, at the moment when the current ceases to pass. It is for the same reason, that the introduction of a bar of soft iron into the interior of the helix, favours the induction of the extra-current. The excellent analysis that M. Masson has made, of his own researches, of those of Jenkins, and of those of Faraday, upon the extra-current, establish a very remarkable analogy between the force of the current, and the discharge of a Leyden jar; an analogy that Faraday had already proved for ordinary induc-

A very important point in our theory is the explanation it gives of the influence exercised over the intensity of the induced current, by the velocity with which the movable conductor is brought near to the fixed one. If this approximation occurs too slowly, the molecular polarisation of the induced conductor is destroyed as fast as it is brought about, without being able to give rise to a sensible current; in order to the production of a current, it is necessary that the + of one of the two extreme molecules of the induced wire should combine, by means of the conductors that connect them with the − of the other extreme molecule, which requires a rapid movement, without which the + and the − of each particle combine together, as soon as they have been separated. This influence of velocity has been appreciated by M. Wartmann who, even when approximating to actual contact, but very slowly, a soft iron armature of a magnet, succeeded in obtaining no inductive current in the wire that surrounded the armature; he was able to obtain the same result by substituting electric currents for the magnet.

We will terminate the additions that we had to make on induction, by the description of a very powerful instrument, contrived and constructed by M. Ruhmkorff, and of which we shall frequently have occasion to make use, in the Fourth Part of the Treatise. This instrument (*fig.* 176.) consists of a very long bobbin, of above 12 or 15 in., surrounded by two wires wound in a helix; the larger one is intended for receiving the inducing current, and in the other which is finer, the induction current is produced. The rheotome is also founded upon the attraction of a small piece of soft iron, by the electro-magnet of the bobbin — an attraction, which by breaking the inducing circuit causes the magnetisation to cease, and, consequently, itself re-establishes the circuit.

tive currents, and which agrees very well with the explanation we have endeavoured to give, of the induction of these currents. We shall, however, return to this subject, and especially to the researches of M. Masson, when we are studying the physiological effects of inductive currents, to which this philosopher has devoted a great portion of the work, of which we have been speaking.

The wires are insulated by means of either silk or resin, and a commutator enables us to change at pleasure the direction of the inducing currents. The discharges given by this apparatus are of alarming intensity; and the light produced by the passage, *in vacuo*, of the discharge from the induced wire, is of remarkable magnificence. In order to increase the power of the apparatus, M. Fizeau conceived the idea of adding to it a condenser, the two plates of which being bent around each other, and separated by an insulating stratum of waxed silk, communicate respectively with either end of the inducing wire, so as to become charged when the circuit is interrupted, and to be discharged when it is re-established, which greatly increases the power of the current, the discharge having the same direction as the current.

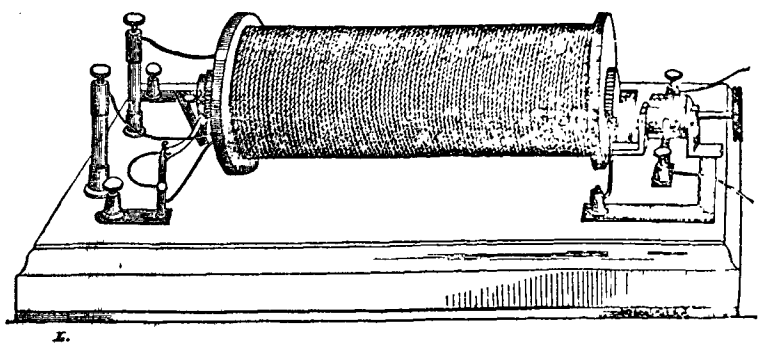

Fig. 176.

III. *Additions to the Chapter relating to the Action of Magnetism upon all Bodies.*

We have described in detail in this Chapter the works of Faraday, of Plucker, and of several other philosophers, on the magnetism and diamagnetism of bodies; but since our publication, new works have appeared, to enrich this branch of physics; and we have ourselves arrived at a theory, which seems to us to possess the advantage of embracing, under the same general principle, all the phenomena that are due to the magnetic power. It is these new researches and

this theory, that we desire to explain in this place, in order to complete what we have already said on this subject, in the Sixth Chapter of our Third Part.

1st.—*New Researches relative to the Action of the Magnet upon all Bodies.*

First we will give a Table, drawn out by M. Plucker, of the numerical results that he obtained by magnetising successively electro-magnets with currents of different intensities; this Table demonstrates the variations, that occur in magnetic attractions and repulsions with the intensity of the current:—

	Current of a single Grove's Pair; an Intensity = 1.	Current of an Intensity 4 times greater.
Iron - - - -	1,000,000	1,000,000
Cobalt - - - -	1,008,900	912,200
Nickel - - - -	465,700	350,900
Oxide of iron - -	758	954
Oxide of nickel - -	286	405
Hydrated oxide of cobalt -	2·178	5·015
Bismuth - - -	23·6	39·03
Phosphorus - - -	16·45	27·31

We will now pass on to the latest researches of M. E. Becquerel. Instead of employing the ordinary balance, and estimating by weights, the specific magnetism and diamagnetism of bodies, M. E. Becquerel, as we have previously said, made use of the torsion balance, placed over the poles of an enormous electro-magnet, upon which it rests. To check the continual oscillations of the extremity of the tension thread that sustains the bar, the subject of experiment, he suspends to the middle of this bar, by means of a double-woven thread, a small leaden ball immersed in water at a distance of a little more than half an inch; it is easily proved that the presence of this sphere introduces no disturbance to the observations, which are thus made with much more precision. A microscope fixed to one of the sides of the torsion-balance, carries a micrometer in the focus of the eye-piece, to which

are successively brought, by torsion, the bars that are the subject of experiment, after having taken the precaution to trace a cross at the end of each of them, to serve as the point of reference. The number of degrees of torsion necessary in order to bring back the point of crossing to the centre of the micrometer, are measured; and thus the exact measure is obtained of the effect due to the action of the magnet; to be freed from causes of error the direction of magnetisation in the electro-magnet is changed, by means of a commutator, and the effect produced is again measured, which is almost always identical with the first observation. Finally, the constancy of the current employed, is insured by means of a sine-galvanometer, placed in the circuit.

M. E. Becquerel moreover proposed to determine the value of magnetic actions in different media, always setting out from the principle that all bodies are magnetic, after the manner of iron, and that the attractive or repulsive effect observed is due to the difference existing between the specific magnetism of a body and that of the medium in which it is placed. But, whatever theory be adopted, the numbers obtained by M. Becquerel remain not the less as important data to be preserved. In order to have a fixed term of comparison, he has referred all the determinations to the specific magnetism of water in air, which he has made equal to -10, water being repelled by the magnet in air, and also *in vacuo*. Finally, by measuring the action of the magnet upon two bars, one of sulphur, the other of white wax, placed, first in air, and then in different media, he deduced the specific magnetism of these different media, as well as that of the sulphur and the wax, in respect to equal volumes; by making use of the rod of sulphur, the results to which he arrived are almost identical for each medium, with those that were furnished to him with the rod of wax.

The following are two Tables, which contain the numerical determination of the action of the magnet upon different substances of the same size, placed in the air; these numbers express, therefore, according to M. E. Becquerel, the action of the magnet upon the body placed *in vacuo*, minus the

action of the magnet on an equal volume of air. The sign — indicates a repulsion; the sign +, an attraction: —

Water	— 10
Ordinary zinc	— 2·5
White wax	— 5·68
Sulphur, sublimed, then melted	— 11·37
Plumber's lead	— 15·28
Phosphorus	— 16·39
Selenium	— 16·52
Bismuth	— 217·60

The relative values between zinc and white wax being more feeble than those which refer to water, these two substances ought to be attracted by the magnet in water; they are actually so, as in almost all liquids.

The following Table, constructed on the same basis as the preceding, contains the results relative to liquids and saline solutions: —

Water (density = 1)	— 10·
Concentrated alcohol (density = 0·8059)	— 7·89
Sulphuret of carbon	— 13·30
Chloride of sodium (density = 1·2084)	— 11·28
Chloride of magnesium (density = 1·3197)	— 12·05
Crystallised sulphate of copper of commerce (density = 1·1265)	+ 8·14
Sulphate of nickel (density = 1·0827)	+ 21·60
Protosulphate of iron, prepared with the crystallised sulphate of commerce (density = 1·1923)	+ 211·16
Protosulphate of iron, prepared with sulphuric acid and iron (density = 1·1728)	+ 180·22
Protochloride of iron, No. 3. prepared with hydro-chloric acid and iron (density = 1·0695)	+ 91·93
Protochloride of iron, No. 1. (density = 1·2767)	+ 360·70
Protochloride of iron, No. 2. concentrated (density = 1·4334)	+ 658·13
Protosulphate of iron, with slight excess of sulphuric acid (density = 1·1587)	+ 137·70

In this last Table which contains only liquids, the effect has been determined by the difference that these solutions experience on the part of magnetism, by means of a solid substance always the same, subjected to the action of the magnet, while

plunged in the different liquids. We arrive at the same results, whatever solid body may be employed for these determinations, providing it remains the same in all the comparative experiments.

All the numbers in these two Tables are referred, as we have said, to volumes; by dividing them by the densities, we should obtain the magnetic power for equal weights. This operation was gone through in M. Plucker's table; it seems useless to repeat it here, seeing that the results obtained by these two philosophers differ too much for any useful comparison to be made between them. We may add that, on mixing very fine and very pure iron-filings, in various proportions with white wax, and forming of it small cylinders about two inches long, and half-an-inch or less in diameter, M. Becquerel, by comparing the action exercised upon them by the magnet with that which occurred on a tube of the same size filled with protochloride of iron, succeeded in determining the magnetic powers of proto-chloride of iron and of water in respect to iron of equal volume and weight. In order to arrive at this determination, he sought by trials for the proportion of iron that ought to be contained in the cylinder of wax, so that it might experience the same action as the equal volume of proto-chloride of iron; he found that it was about ·003 gr. Troy, to ·061 cubic in. whence he deduced the following magnetic powers for equal weights: —

Iron - - - - -	+ 1,000,000
Proto-chloride of iron - - -	+ 140
Water - - -	— 3

We have also to report the important results, to which M. E. Becquerel arrived, in respect to the magnetic properties of gases, results that he obtained by observing the repulsion exercised by the poles of the electro-magnet upon a very thin bar of glass, closed at its two extremities by the blowpipe, plunged successively into different gaseous media; this bar was 1·37 in. long, ·27 in. in diameter and weighed 11·45 gr. Troy; it was slightly magnetic. In the air, it

was less attracted than *in vacuo*, which seemed to indicate that air was a magnetic medium. The attraction of the glass being diminished in the air, the repulsion of a diamagnetic body, such as sulphur, ought on the contrary to be stronger in air than *in vocuo*; and this is confirmed by experiment. Hydrogen, nitrogen, carbonic acid give no appreciable effect of this; but oxygen manifested the same property as air, and this with an intensity five times greater; which proves that it is its presence which gives to air its magnetic property, and the more so as nitrogen is insensible to this action. Here, then, is a direct experimental proof that oxygen is attractable by the magnet, in the same manner as iron; and that it is even very strongly magnetic.

In order to determine more accurately the magnetic power of oxygen, M. Becquerel took a small glass tube, which he filled with melted wax; the glass being slightly attracted and the wax repelled by the electro-magnet, he thus obtained a body very nearly indifferent, being just slightly diamagnetic. He determined the effect of the magnet upon the glass tube *in vacuo*, in air, in oxygen and in water, and he found: —

In vacuo	— 0·1145
In oxygen	— 0·2675
In air	— 0·1453
In water	+ 0·7033

which gives for the magnetic force of oxygen in respect to water *in vacuo*, + 1·871, and in respect to water in air, + 1·80. Thus with equal volumes and at the pressure of 30 in. the magnetic power of oxygen is half that of water; but taken with the contrary sign, oxygen being attracted by the magnet, whilst water is repelled, a slightly different method gave 1·73 instead of 1·80.

Finally, M. E. Becquerel studied the action of the magnet upon gases, by condensing them into a porous substance, such as charcoal. He prepared cylinders of oak charcoal, an inch to an inch and a quarter in length, and a third of an inch in diameter, which were calcined to redness in

sand, before each experiment. Repelled *in vacuo*, these cylinders were strongly attracted in air, and especially in oxygen, of which they absorb about nine times their own volume. It is probable that the very various results obtained by different philosophers in respect to the action of the magnet upon charcoal in air, are due to its absorbing air and water, and on which account it must experience different effects according to the proportion of these substances, the air giving to it an attracting and the water a repelling power. The trials made with other gases furnished results that were too undecided to furnish conclusions, with any degree of accuracy, as to the magnetic or diamagnetic power of these gases. It is otherwise with oxygen and with air; so that we may regard the following conclusions as sufficiently near to truth, namely that the specific magnetism is for —

	Equal Volumes.	Equal Weights.
Oxygen at the pressure of 30 in. - -	+ 1·80	+ 1257
Air - - - - - - - -	+ 0·38	+ 293
Water - - - - - - -	— 10·00	— 10

On comparing these values with iron, from the table given above, where, for equal weights we had, for water — 3, iron being 1,000,000, we obtain for specific magnetism in respect of equal weights: —

Iron - - - - -	1,000,000
Oxygen - - - - -	377
Air - - - - - -	88

We had obtained for the most magnetic liquid (protochloride of iron) + 140, iron being 1,000,000; so that oxygen is, weight for weight, three times more magnetic than the most magnetic of liquids; therefore, after the magnetic metals (iron, cobalt, and nickel), this body is the most magnetic, weight for weight.

The following is a Table containing the last results obtained by Faraday on the magnetic and diamagnetic powers

of certain bodies by employing a large magnet, constructed by M. Logeman, according to the principles of Dr. Elias, which weighs a little more than 100 lb. and which is capable of supporting 430 lb. In this Table, the angles of torsion necessary to balance the attractive and repulsive force of the magnet, express the magnetic and diamagnetic powers of the various substances, volume for volume: —

Proto-ammo. of copper	134°·23
Per-ammo. of „	119 ·83
Oxygen	17 ·5
Air	3 ·4
Olefiant gas	0 ·6
Nitrogen	0 ·3
Vacuum	0 ·0
Carbonic acid gas	0 ·0
Hydrogen	0 ·1
Ammonia gas	0 ·5
Cyanogen	0 ·9
Glass	18 ·2
Pure zinc	74 ·6
Ether	75 ·3
Alcohol absolute	78 ·7
Oil of lemons	80
Camphor	82 ·59
Camphine	82 ·96
Linseed oil	85 ·56
Olive oil	85 ·60
Wax	86 ·73
Nitric acid	87 ·96
Water	96 ·6
Solution of ammonia	98 ·5
Bisulphate of carbon	99 ·64
Sat. sol. nitre	100 ·08
Sulphuric acid	104 ·47
Sulphur	118
Chloride of arsenic	121 ·73
Fused borate of lead	136 ·6
Bismuth	1967 ·6

M. Plucker, who had at first thought that air and oxygen were diamagnetic, recognised afterwards the magnetism of oxygen; he also proved that two of the nitrous compounds were magnetic; namely, the deutoxide of nitrogen and

nitrous acid in the state of gas, which is due probably to their being less powerful combinations than the others; he also remarked that the presence of a small quantity of free oxygen in a gas is sufficient to make it attractive to the magnet.

We may also remark that M. Plucker came to the conclusion, as did M. E. Becquerel and Mr. Faraday, that the magnetism of oxygen, and in general of magnetic mixtures and combinations, is proportional to the density of the gas. He operated in all his experiments with a bubble of glass, the feeble magnetism of which was compensated by that of the surrounding air, so that the action of the magnet upon the bubble empty of air was perfectly null; it was 1·77 in. in diameter, and at the ordinary pressure contained a volume of oxygen, weighing only 0·87 gr. The attraction exercised upon this gas by the electro-magnet was equivalent to a weight of 0·308 gr., which gave M. Plucker for the specific magnetism of oxygen, compared weight for weight with iron taken as unity, ·0003500 instead of ·0000377, found by M. E. Becquerel. Mr. Faraday, in the Table we have just introduced, gives 17·5 for the magnetism of oxygen, the diamagnetism of water being 96·6; which leads to + 1·81 for oxygen, water being — 10. But this result is perfectly in accordance with that of M. E. Becquerel (p. 29.); a proof that his number, and not M. Plucker's, should be accepted.

Thus, it follows equally from the experiments of MM. E. Becquerel, Faraday, and Plucker, that oxygen is a body eminently magnetic; and that with respect to other gases, if we except some that are magnetic on account of the oxygen they contain, the greater numbers do not experience from the electro-magnet any kind of action, the diamagnetism, which we suppose we have remarked in them, being apparent only, and arising, as we have said, from the experiments being made in air, which is a magnetic fluid.

We have described the works of MM. Tyndall and Knoblauch on magneto-crystalline phenomena; since that time Mr. Tyndall has added some new facts in confirmation of the very simple and ingenious theory, which makes the

effects, produced by the action of the magnet upon crystals, to depend solely upon the particular mode of the groupment of their particles. This clever philosopher has in particular succeeded in imparting to solid substances by strong pressure, and without the necessity of reducing them to powder, a molecular state, which causes them to assume, between the poles of an electro-magnet, a direction depending upon the direction of the pressure, that has been exercised upon them.

M. Matteucci obtained the same effects from compression, both upon sulphur and upon stearic acid, as well as upon bismuth. The pieces submitted to compression were placed between two glass cheeks in a vice, so that all the points of their two surfaces were equally compressed; they were then washed in hydrochloric acid to free them of all impurity; the form of cubes had been given to them; and these cubes, being suspended, so that the line of compression was horizontal, constantly took a direction between the poles of the electro-magnet, so that this line was perpendicular to the polar line. On taking a cube of 0·39 in., and cutting from the side that had been strongly compressed prismatic needles in different directions, they directed themselves equatorially or axially, according as the line of compression, was parallel or perpendicular to their axis, which depends on the manner in which they have been cut. If the prismatic needles are cut from masses of crystallised bismuth, very decided differences are observed between them, according as their cleavage faces, which are always parallel to their length, are horizontal or vertical. Thus, three needles of the same length (0·72 in.), but of different weights, from 17¼ to 126 grains Troy, suspended between polar surfaces 1·37 in. apart, always made the same number of oscillations in a time sensibly shorter, when the cleavage faces were vertical, than when they were horizontal: the one that was 126 grs. in weight, made 20 oscillations in 52 seconds in the former case, and in 136 seconds in the latter. If the polar extremities are elongated into a point, the differences are less. When the

planes of cleavage are perpendicular to the axis, the needle directs itself axially between the poles, providing the polar extremities are not too near together, in which case it is repelled toward the equatorial line.

M. Matteucci succeeded in imitating all the effects of crystallised bismuth, by forming cubes and needles, by means of small very thin plates of bismuth, obtained by dropping liquid bismuth in small drops from a certain height upon a marble plane: this is one more proof that the cleavage planes act as separated plates. Moreover, M. Matteucci felt a difficulty in explaining all magneto-crystalline phenomena by the theory of MM. Tyndall and Knoblauch; he does not see to what, in this theory, he must trace the very great difference of the repulsive force, that causes a needle of bismuth to oscillate, whose planes of cleavage are parallel to its axis, according as these planes are vertical or horizontal. He also finds the following experiment far from reconcilable with this theory; when, having suspended between the poles of the electro-magnet a needle of sulphate of lime, to the extremities of which are fixed two cubes of bismuth, he saw the needle always repelled in the equatorial line, when the cleavage faces were either horizontal or parallel to its length; and, on the contrary, travel to the line of the poles, when the cleavage faces were perpendicular to the length of the needle. The polar faces in this case were square, and 2 in. apart. This experiment does not appear to us, as it did to M. Matteucci, contrary to the theoretical ideas of M. Tyndall; in fact, the two cubes of bismuth, when the needle of sulphate of lime is placed axially, have their planes of cleavage perpendicular to this line, as ought to be the case. It is true that they seem to be attracted by the magnetic poles, whilst the bismuth, naturally diamagnetic, ought to be repelled; but if the needle, which carries the two cubes, is placed equatorially, then the cleavage planes would be parallel to the axial line, which would be contrary to theory. There is in this case, therefore, an opposition between two contrary tendencies; and, if the influence of the cleavage plane has the superiority, it is due to the size of the

magnetic field, which is itself due to the extent of the polar surfaces, and to their distance.

With regard to the influence of the horizontal or vertical arrangement of the plane of cleavage upon the diamagnetic power of a crystal of bismuth, it is very probably due to an effect of induction. M. Matteucci has appositely made the very curious remark, that of two perfectly equal cubes of crystallised bismuth, subjected to the action of a rotating electro-magnet, the one whose cleavage planes are vertical and perpendicular to the planes of the current of the electro-magnet, is drawn in with much more force than is that, whose cleavage planes are horizontal: in all cases, amorphous masses of bismuth experience a more considerable action than those, that are crystallised. The difference is still more sensible when, instead of cubes of crystallised bismuth, we take two cubes formed of very thin plates of copper, insulated from each other by a coat of varnish. The cube whose plates are vertical assumes a very rapid rotatory motion, under the influence of a rotating electro-magnet over which it is suspended; whilst the one whose plates are horizontal does not feel the action of the electro-magnet. It appears that, in the former arrangement, the induced currents may be freely developed, and can circulate in each plate, which is not the case with the second arrangement, in which the induced currents do not possess for the completion of their circuit any conductor beyond the inducing influence.

Matteucci's experiments point out, as Faraday had previously remarked, the important part induction may play, when the action of the magnet upon conducting bodies is being studied. This part may even be manifested in cases where beforehand we should not have thought it possible. The following are some curious examples, which we also owe to Matteucci. Having obtained copper, silver, and bismuth in a state of extreme division, by decomposing very pure solutions of these metals with a very powerful battery, he first satisfied himself, by placing these metallic powders in tubes of straw or quill, that they were very powerfully diamagnetic; he then made of them homogeneous mixtures by mixing

them rapidly with melted resin. These mixtures were diamagnetic and perfectly insulating, as might be proved by placing them with a sensitive galvanometer in the circuit of a powerful battery. However, spheres of 0·47 in. in diameter, formed of these mixtures of resin and metallic powders suspended by a cocoon thread at a very little height above the poles of an electro-magnet that was set rotating, turned in the same direction as this electro-magnet, accomplishing in this way several revolutions. This effect could not be due to the diamagnetism of the mixtures, for phosphorus and stearic acid, which have a much higher degree of diamagnetic power, do not acquire the magnetism of rotation under the action of the same electro-magnet. On the other hand, it was difficult to attribute this rotation to induced currents, similar to those which are developed in continuous metallic masses, for the particles of which these powders are composed are less than 0·00039 in. in diameter. However, it is clearly in induction that we must seek for the explanation of these phenomena; and the proof is, that the mixtures, formed with the powders of silver and of copper, manifest them with more intensity than those which contain divided bismuth, a metal that is not so good a conductor: the powders made with the oxides of the same metals, which are not conductors, do not produce any effect. It is probable, therefore, that a molecular induction is brought about in the particles, which gives rise to a molecular current when the particle is insulated, and to a finite induced current when several particles are agglomerated, so as to form a continuous mass. We should find in this a remarkable confirmation of the theory of induction that we have given above.

2nd.— *General Theory of the Phenomena that are due to Magnetic Power.*

For a long time, led to be regarded as only a special action, being exercised upon a very small number of bodies, the action of the magnet is now universal, namely, all bodies are susceptible of experiencing it. It is true that it is manifested

under divers forms, but these forms themselves are connected together and are attached to one general principle; this is the point, that we shall now endeavour to establish. But, in the outset, we must call to mind that the action of the magnet is identical with the action exercised by closed electric currents exteriorly to the circuit which they are traversing; this is now generally admitted by all philosophers, for this identity rests at once upon mathematical and upon experimental proofs, and particularly upon the fact that the two species of action may in all cases be substituted for each other, to produce the same effects under the same circumstances.

The various forms under which the action of the magnet, or that of closed electric currents, is manifested, may be reduced to four principal heads.

1st. Action upon magnetic bodies, which consists of an attraction, a directive force the consequence of this attraction, with a magnetic polarity.

2nd. Action upon diamagnetic bodies, which consists of a repulsion, and a directive force the consequence of this repulsion, but without sensible magnetic polarity.

3rd. Action upon transparent bodies, both solid and liquid, which consists of the property they acquire under the influence of this action, of rotating the plane of polarisation of a ray of polarised light that traverses them, through a greater or less angle.

4th. Action upon all very good conducting bodies, which consists in the development in these bodies of instantaneous currents, called currents of induction.

If we endeavour to discover the common and characteristic properties on the one hand of magnetic bodies, and on the other hand of diamagnetic, we find that the former are they which, volume for volume, contain the greatest number of chemical atoms, and the latter they which contain the least. This law which had been already noticed in reference to magnetic bodies, when only *iron*, *nickel*, and *cobalt* were reckoned among magnetic metals, is found to acquire a remarkable confirmation and generalisation, since Faraday has added to the list of these metals, *manganese*, *chromium*,

titanium, cerium, palladium, platinum, and *osmium.* In fact, whilst the three former metals contain under the same volume 230 atoms, the seven following 170, the diamagnetic metals, as *gold* and *silver,* contain only 150, *antimony* and *lead* 85, and *bismuth* only 74.* Two metals alone are an exception; *copper,* which contains 230 atoms, and *zinc,* 170; but these two metals are excellent conductors of electricity, whilst all the other metals of the two same categories, which are magnetic, are very bad conductors. It would therefore appear that the magnetic power would be a direct function of the number of atoms contained in the same volume, and inversely to the electric conductibility; on this account it is that *gold* and *silver* should each of them be diamagnetic, and not magnetic; they are so in fact, together with copper and zinc, which are the best conductors of electricity, and they moreover contain only 150 atoms, volume for volume, instead of 230 and 170.

Diamagnetic bodies would therefore be those which, volume for volume, contain the smallest number of atoms, or which, if they contain more, are very good conductors of electricity. It is remarkable that these latter are very slightly diamagnetic, and consequently very near the limit; and that even, as we shall see hereafter, they may under certain circumstances become magnetic. But an important point to be noticed is the relation existing between the diamagnetism of bodies and their magnetic rotatory power. It is in error that several philosophers, who have been engaged upon this subject, have regarded these two properties as independent of each other. From the very commencement of these researches, Faraday had happily recognised this dependence; and it is not without reason that, after having discovered that the influence of magnetism caused the plane of polarisation in a prism of heavy glass to rotate, he found that this prism directed itself equatorially between the poles of the electromagnet.

The following then are the relations, that connect these

* For the calculation of these numbers, the atomic weights deduced from the specific heats have been taken.

two properties with each other. The former, which is the position that the diamagnetic body assumes in order to escape from the action of the magnet, namely, the equatorial position, is that in which the body ceases to possess rotatory magnetic power, supposing that the polarised ray always traverses it in the direction of its length. The latter is that all the circumstances, which increase in the same body the rotatory magnetic power, equally increase its diamagnetic power. Thus M. Wiedemann demonstrates that the rotation of the plane of polarisation is proportional to the intensity of the current, or of the magnet that is acting upon the substance; and we have seen, on the other hand, that the diamagnetism is in like manner proportional to this intensity. We know that crystals have a very feeble rotatory magnetic power: now their diamagnetism is also feeble on account of their molecular constitution, which causes them to be directed sometimes axially instead of equatorially. The third relation is that substances, which by their nature have the greatest amount of diamagnetism, are also they which exercise the most powerful rotatory action upon the plane of polarisation; and reciprocally, the more a substance is magnetic, the less decided is this action. This fact is derived from the experiments of M. E. Becquerel, and from those of M. Bertin. Thus the rotatory power and the diamagnetism of water being each of them 10, chloride of magnesium has 16 for its rotatory power, and 12 for its diamagnetism; sulphuret of carbon, 29·3 and 13·3; chloride of calcium 16 and 11·6. With regard to magnetic bodies, sulphate of nickel has 13·55 for its rotatory power, and 21·60 for its magnetism; diluted protochloride of iron 9·45 and 92; and concentrated protochloride of iron 3 and 6·58. The fact observed by M. Mathiessen, that when a glass contains a magnetic metal, but in such small quantity that its transparency is not too much altered, the rotation increases with its thickness, is not opposed to the law that we have just laid down; for in this case the body that acts upon the light is not magnetic crystal, but glass; and the metal only seems to transmit into the interior of the glass the magnetic power, that emanates from

the poles by which it is itself magnetised. I have myself submitted a great number of liquid substances to the action of the electro-magnet, in order to determine their relative diamagnetism by means of a torsion balance, to the wire of which were suspended tubes of very thin and very white glass, filled successively with the different liquids; and I constantly found that the order of their diamagnetic power was the same as that of their rotatory magnetic power. The numbers, it is true, that express the two powers, are not proportional; but this is not to be wondered at; for, seeing the very different form of the two phenomena manifested upon the substance by the action of the magnet, it is impossible to admit that the two results are the same function of forces put into play in this double action.

We have nothing to add to what we have already said upon induction; we have merely to repeat that its intensity is a function of the conductibility of bodies for electricity, and that it depends consequently both upon their dimensions, and the greater or less conducting power of their particles.

After having thus analysed the phenomena, that are due to the action of the magnet, and having endeavoured to establish the relations and differences, that exist between them, it remains for us to seek for a theory, which may collect them under one and the same general principle.

The first point that I wish to establish is that diamagnetism is not a magnetism relatively more feeble. I have already combated this opinion, which assimilates diamagnetism to magnetism,— an opinion that had strongly induced M. E. Becquerel to admit that vacuum is magnetic, and is more so than a very great number of bodies: I shall not, therefore, return to it; I shall merely add that there have never been found in diamagnetic bodies, when they are under the influence of powerful magnets, any traces of poles, such as they ought to acquire, if these bodies are really endowed with magnetism. It is true, on the other hand, that some experimentalists think they have detected contrary poles to those which they ought to have according to M. E. Becquerel's theory; namely, poles of the same

name as the magnetic poles nearest to them; which would make diamagnetism seem to be the antagonism of magnetism. We have already given the experiments by which Poggendorff, Reich, and Weber thought they had demonstrated that magnets determine in diamagnetic bodies polarity homogeneous to their own. We have seen that these experiments might receive another interpretation; and that, in particular, their effects were essentially due to the production of induction currents over the surface of the metals submitted to the influence of electro-magnets, or merely to that of closed currents. But Weber took up the subject anew and arrived at results, that really seem favourable to the idea of diamagnetic polarity. In this work, in which he has discussed with remarkable care all magnetic and diamagnetic phenomena, while attributing the former to molecular currents pre-existing around the particles and only movable with them, according to Ampère's theory, he is led to consider the latter as depending upon the existence, in the interior of the bodies, of electric fluids put into the state of current by a powerful exterior cause, such as the poles of an electro-magnet. In this case, the currents would not pre-exist, and would not be connected in an indissoluble manner with the particles, as in the case of magnetic bodies. But he was still led by his theory to admit a diamagnetic polarity, the inverse of magnetic polarity. Two series of experiments seem to him to prove the existence of this polarity. In the first, a long helix is placed vertically between the two poles of a very light horse-shoe magnet, and delicately suspended by a vertical silk thread, fixed by its lower extremity to the middle of a cross-piece which unites, near the bend, the two parallel branches of the magnet, which is situated in a horizontal plane. When the helix is traversed by the current, all is symmetrical in every respect; the magnet does not move, the two poles being equally either attracted or repelled by the helix, according to the direction of the current that traverses it; but if a cylinder of bismuth is made to move in the interior of the helix, we observe, setting out from the position in which the middle of the cylinder is in the plane of the

magnet, that if we raise it the magnet moves in one direction, and that if we lower it it moves in the other direction, which seems to indicate two opposite poles at the extremities of the cylinder. With an iron wire, substituted for the bismuth, the same movement is observed, but in an opposite direction. But what is singular is that a similar movement, and almost equally powerful, occurs when the bismuth is moved in the helix, without the latter being traversed by an electric current; only the movement occurs in an opposite direction: it is more powerful when the bismuth is raised than when it is lowered, which is the reverse of what happens when the helix is traversed by the electric current. It is evident that, in these experiments, the bismuth experiences a modification in its magnetic or electrodynamic relations, from the mere circumstance of its being surrounded by electric currents: this is not astonishing; since, if it were transparent, this modification would be detected by the rotation of the plane of polarisation. The whole of these experiments, in fact, seem to prove that this modification consists in the production of a polarity such as Weber conceived. However, how are we to explain the action of the bismuth, when it is not surrounded by electric currents? In this case, it ought to repel equally both poles of the movable magnet; and the latter, consequently, ought to have no movement. Finally, in order to be quite assured that the induction currents played no part in this new form, given to these experiments, Weber ought to have employed other metals besides bismuth, and to have shown that the effects obtained are less with metals that are less diamagnetic.

The same observation applies, and with still greater force, to the second series of Weber's experiments. In this series there are two concentric helices, well insulated from each other; the outer one is traversed by an electric current, the inner one is placed in communication by its two extremities with a galvanometer; and a cylinder of bismuth is moved within it. Care is taken to wind one half of the spiral of this interior helix in a contrary direction to that of the other half, so that the inductive effects, pro-

duced by the successive introduction of two different magnetic poles, may be added together. The experiment is conducted in such a manner that a commutator sets the bismuth in motion at the same time that it changes the communications of the helix with the galvanometer, so that the induction currents always travel in the latter in the same direction, and their effects are consequently added together. A series of induced currents is thus obtained, which are detected by their action upon the galvanometer; and, by substituting an iron wire for the rod of bismuth, we also obtain currents, but, under the same conditions, moving in opposite directions. We might, perhaps, propose to M. Weber the objection that the presence of the cylinder of bismuth ought to modify the action of the exterior helix upon the interior, and consequently explain the development of the currents, that are detected by the galvanometer. In this series of experiments, as well as in the former, M. Weber ought to have employed not only other metals besides bismuth, but also metals drawn into thin wires and made up into bundles, in order to compare their effects with those of similar metals forming solid cylinders; which is the only mode of thoroughly distinguishing the effects due to polarity from those which arise from induction currents, developed upon the surface of masses introduced into the helix.

The fact of diamagnetic polarity appears to us however to have been very well established by M. Weber's recent researches, although there are still against him certain negative facts, such especially as those recently pointed out by M. Matteucci. This philosopher constructed four helices perfectly similar, which he arranged vertically at the four corners of a square wooden slab; an astatic needle was delicately suspended in the middle of the four helices; and the apparatus was so constructed that no motion was produced upon the needle, when a discharge or a series of discharges passed in the helices. He had merely to fill the interior of the two helices placed at the extremity of one of the diagonals with a mixture of wax and small quantities of colcothar (oxide of iron) in order to obtain very marked effects at the moment when the discharge was passing. By substituting cylinders

of bismuth for the magnetic cylinders, not the slightest motion of the astatic needle was obtained. However, the diamagnetic power of bismuth was far superior to the magnetic powers of the mixture of wax and colcothar; which seems to prove that diamagnetism is not the result of a polarity of the same kind as magnetic polarity. M. Matteucci also proved that by employing non-conducting diamagnetic bodies, such as phosphorus, sulphur, or stearic acid, instead of metals, no inductive effect was produced either in one direction or in the other. We shall see further on that the interesting facts observed by Matteucci are not in opposition to the existence within diamagnetic bodies of a particular species of polarity.

Mr. Faraday does not admit of diamagnetic polarity; we have already said that he regards the action exercised by magnets upon magnetic and diamagnetic bodies as the results of forces emanating from the poles of magnets, according to certain directions, and which he calls *lines of force*, and the whole of which constitute the magnetic field. The presence of a body in this magnetic field modifies the directions of the lines of force: if the body is magnetic, it concentrates the lines of force; if diamagnetic, it makes them diverge. This modification, brought about in the distribution previously uniform of these lines of force, gives rise to attractive movements for magnetic bodies, and repulsive for diamagnetic. Mr. Faraday entered into a detailed study of the magnetic field, and the direction of the lines of force, a very exact idea of which is given by the distribution of iron filings around and between the poles of magnets. We have already seen that he succeeded in employing induction to demonstrate the equality and the distribution of these lines of force in the magnetic field. It follows indeed from the experiments to which we have referred in the chapter on induction that, at whatever distance from the magnet these lines are cut, the induction current, collected by the movable wire by which they are cut, possesses the same intensity; which proves that magnetic force has a definite value, and that for the same lines of force, this value remains the same at all distances from the magnet: neither the convergence or divergence of the lines, nor yet the greater or less obliquity of the intersection introduces any difference

into the sum of their power. The study of the internal part of the magnet leads us to recognise that the lines of force have there also a definite power, and perfectly equal to that of the exterior lines, which are only the continuation of the others; and this whatever the distance may be, which may be infinite, to which they are prolonged.

We must not forget that Mr. Faraday, by the term lines of magnetic force, expresses the power of the force of magnetic polarity, and the direction according to which it is exercised. If the magnetic field is composed of equal forces equally distributed, as may easily be obtained with a horse-shoe electro-magnet, we have merely to place a sphere of iron or nickel in this field, to cause an immediate disturbance in the direction of the lines of force. The forces are not only concentrated, but are bent or modified in their direction by the metal spheres that are introduced; they experience a convergence upon the opposite faces of a magnetic sphere and a corresponding divergence upon the opposite sides of a diamagnetic sphere. It is this property that Faraday expresses by the words *conduction polarity*. Temperature diminishes the power possessed by bodies of affecting the direction of the lines of force, and even causes them to disappear at a certain point. This may be proved by observing that a small magnetised needle, about the tenth of an inch in length, which always places itself parallel to the lines of force, in the different points of the magnetic field, first changes its direction near spheres of iron or nickel, then recovers its parallelism when the two spheres are raised to a sufficient temperature. The oxygen of the air, which, in virtue of its magnetic properties, ought to modify the direction of the lines of force of terrestrial magnetism, loses in great part also this property by the elevation of temperature, which furnished Mr. Faraday, as we shall see, with an ingenious explanation of the diurnal variations of the magnetised needle.

The few words, that we have been devoting to Faraday's theoretic ideas, are sufficient to make them understood: the fundamental idea of the illustrious philosopher is in the main the negation of all action at a distance, and the explanation of the phenomena by continuous force, forming what he calls

lines of force. Bodies, by their presence, modify these lines of force; and there arise directive motions, which are manifested by the disposition of these bodies to place themselves according to their nature, either axially or equatorially, namely, in the places where the force is A its maximum, or in those where it is at its minimum. A learned English philosopher, Mr. Thomson, on applying calculation and notions of mechanics to Faraday's ideas, found that they represented, in a remarkably exact manner, what takes place in this order of phenomena, providing we take into account the mutual action of the parts of which the bodies are composed that are submitted to magnetic influence. Mr. Thomson has also made a great many experiments upon small wires, and upon cubes of iron, arranged in different manners, by suspending them near to or within a ring traversed by an electric current; and he always perceived that these bodies placed themselves parallel to the lines of force.

We cannot altogether acquiesce in Faraday's ideas, however ingenious they may be. Does the magnetic field really exist, as the learned philosopher conceives it to be, namely, independently of the bodies by which its existence is made manifest? This is the point upon which I have some doubts. I am rather disposed to admit that magnetic forces are exercised only so long as there is a body which determines their manifestation. M. E. Becquerel has already demonstrated that the action of the magnet upon magnetic and diamagnetic bodies is proportional to the square of the intensity of the magnet or of the current, and not to the simple intensity, which shows that these bodies enter, on their own part, into the production of the effect, and that they do not play simply a passive part. Mr. Tyndall arrives at the same conclusion, as the result of numerous experiments, made equally upon diamagnetic and magnetic bodies. He even believes he has found that bismuth acquires a magnetic polarity, analogous to that acquired by iron, but merely transverse instead of longitudinal. He deduces this last conclusion from the results he obtained by surrounding a piece of either ordinary or crystallised bismuth, when suspended in the magnetic field, with a helix traversed by an electric current. He

found, on placing the helix, sometimes parallel at other times perpendicular to the axial line, considerable deviations from the direction which the bismuth ought to take, when not surrounded by an electric helix ; and he considers that these deviations are explained by a transverse magnetism imparted to it by the magnet. But, on the other hand, how is the repulsion to be explained? What can be said with most truth is, as Mr. Tyndall himself remarks, that the presence of the helix, traversed by an electric current, brings into the magnetic field modifications, that cause the greater and the less lines of magnetic force to exchange places, which become inclined to the axial or equatorial direction. Finally, we may remark further, that if the lines of force are sufficient, as Faraday admits they are, to explain all the phenomena, why have these lines need of the intervention of a body in order to act upon the polarised ray, and cannot they act directly upon this ray in vacuo? a result which we have not been able to succeed in obtaining although employing even a very considerable magnetic power.

From this long discussion, we deduce :

1st. That bodies, submitted to the action of magnetic force, undergo modifications which determine the motions they execute under the action of this force, as well as other effects which they become capable of producing, such as the rotation of the plane of polarisation :

2nd. That these modifications are not of the same order in magnetic and in diamagnetic bodies ; in other words, that these latter do not acquire a polarity similar to that acquired by magnetic bodies :

3rd. That, consequently, neither M. E. Becquerel's theory, which assimilates diamagnetic bodies to magnetic, nor Faraday's, which attributes to the bodies only a passive part, appears to us to explain in a satisfactory manner the different forms under which magnetic power is manifested, whilst Weber's theory would seem better to represent this order of phenomena.

Let us inquire, then, whether or not there are any means of attaching this latter theory to a general principle, allowing ourselves to be simply guided by the results of experiment.

When we study electro-chemical phenomena, we are forcibly led, as we shall see, to admit a simple relation between the atom and electricity. Ampère had supposed that each atom of matter possesses an electricity proper to itself either positive or negative, and that, in the state of equilibrium, it is surrounded by an atmosphere of electricity of a contrary nature to its own, and which disguises the latter. This hypothesis, which very elegantly explains a certain number of facts, is open to grave objections; in particular, it does not at all explain how the same atom can be sometimes positive, at other times negative, according to the atom with which it is put in relation, which we must admit, if we would explain a great number of chemical facts. Berzelius had admitted that each atom has two electric poles, one positive, the other negative. He had founded his hypothesis on the existence of these two poles in the molecules of tourmaline and of certain crystals. But to this simple hypothesis, another was added, which was not at all probable, founded upon the fact that there are some conductors which conduct one of the electricities better than the other, an assumption since demonstrated to be inaccurate. This hypothesis was that atoms are unipolar, that is to say, that they keep but one of their electricities in combining together, and abandon the other. We shall see hereafter that this hypothesis is not necessary to the explanation of chemical and electro-chemical phenomena, which may be very well reconciled with the idea of polarity, such as Berzelius had supposed, without any need of adding thereto unipolarity. I am therefore disposed to admit in the atom a natural polarity; all the facts relating to the development of electricity, particularly by heat, seem to lead in this; and with respect to the objection raised, that the atom being naturally spherical, there is no obvious reason that it should have a polarity in one direction rather than in another, we have only to suppose, which is far from being improbable, that each atom of matter originally received a motion of rotation upon itself; and we then obtain for the atom an axis and a direction of rotation, and consequently a different pole at each extremity of the axis.

Setting out from this primitive polarity of the atom, it is easy for us to deduce from it, according to the known laws of electricity, the properties that are manifested by bodies under the action of the magnet or of closed electric currents. We may first remark that, when an atom is isolated, that is to say, at too great a distance to be influenced by the neighbouring atoms, the two electricities, accumulated at the extremities of its axis, ought constantly to unite by its very surface, and this with the greater facility as it is in itself of a better conducting nature. For instance, let *a* (*fig.* 177.), be the atom, *b* and *c*, the extremities of its axis or its two poles; the + electricity, constantly carried to *b*, tends to unite itself by the surface of the atom with the negative electricity that is carried to *c*; there arises, therefore, from this a current going from *c* to *b*, through the axis, and from *b* to *c* on the whole surface of the atom. Thus, we may consider the atom as traversed by a current, that returns to its point of departure, by the surface of the atom itself. The latter is, therefore, in a state of electric equilibrium, since the two currents, one of which traverses, and the other surrounds it, are equal and in contrary directions. But, if a certain number of atoms are approximated to within such a very small distance of each other, that their mutual influence may be exercised, then they become so arranged (*fig.* 178.), that the pole + of the atom *a* is in contact with the pole − of the atom *b*; the + pole of *b*, with the − of *c*; and so on, until they form a chain, of which the last atom, for example, has its + pole in contact with

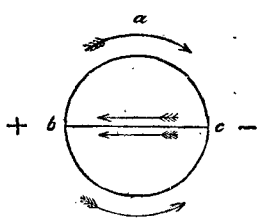

Fig. 177.

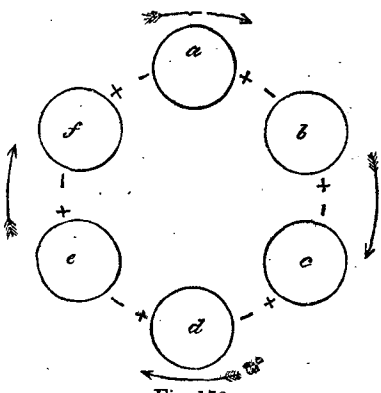

Fig. 178.

the — of *a*. We have thus an integrant molecule, surrounded by one electric current, circulating about it. The number of atoms that enters into its formation, depends upon the molecular constitution of the body, which is not regulated any more than cohesion is, by electric polarity, but which descends probably on the mass of the atom.* In order that this electric current, whose formation we have been describing, may be established around the integrant molecule, the latter must be composed of atoms, that are very near together. Now, which are the bodies that are in this condition? We have seen, at the commencement of this paragraph, that they are the magnetic bodies. Thus, therefore, magnetic bodies are, by the very fact of the approximation of their atoms, bodies each of whose integrant particles, compounded of a greater or less number of atoms, is surrounded by an electric current. In the natural state, the particles, left to themselves, so arrange themselves that all these electric currents mutually neutralise each other; but if we now exert on the magnetic body an exterior action, by presenting to it a magnet or an electric current, we compel the particles so to arrange themselves, that their currents are parallel to those of the magnet, or of the current presented to them. And thus magnetism is produced; it is temporary if the particles do not preserve the position, which the exterior force has impressed upon them, after this force has ceased; it is permanent, if they do preserve it; furthermore, it is the molecular constitution of bodies that determines the more or less decided degree of this property, which we have termed coercitive force. We are thus led *à priori* to Ampère's theory of the constitution of magnets, and to admit that electric currents pre-exist around particles, and that magnetisation simply consists in arranging them in a common direction — a consequence already deduced from the molecular effects that accompany them. We may remark that it is essentially the particles of the surface that experience this effect of direction, which tends, on the con-

* We admit here, with all philosophers, that the difference existing between the chemical atom, and the integrant or physical molecule, is, that the molecule is only an agglomeration of a greater or less number of atoms.

trary, to destroy the influence of the interior particles; and this explains the property of tempering, and why a hollow magnet is more powerful than a solid one of the same volume.

Two metals alone are exceptions to the law that we have just laid down; these are copper and zinc; they ought to be magnetic, according to their atomic volume, and they are not so; it is true that they are only very feebly diamagnetic, but they are diamagnetic. We have already remarked that these two same metals are much better conductors than all those that have the same atomic volume: now this explains to us why they are not magnetic, like the others. Indeed, in order that the electric current may be established around the integrant molecule (which is the characteristic of a magnetic body), it is not only necessary that the atoms be very near together, but also that they be not of a nature sufficiently conductible to enable the electricities accumulated at their two poles easily to unite by means of their surface, even when they are insulated, rather than to unite with the contrary electricities of the two atoms, between which each of them is interposed. Now this actually occurs with the atoms of copper and zinc, on account of their great electric conductibility. And so copper may be rendered magnetic, by combining it with oxygen or chlorine, which diminish its conducting powers.

The very decided magnetism of oxygen is explained by admitting that each molecule of oxygen is formed of a very dense group of elementary atoms; an hypothesis that confirms, as we shall see, the ozonised condition of oxygen that is obtained on disaggregating its particles. It is very remarkable that oxygen, which is the only magnetic gas, is the only one also whose particles can be disaggregated.

We may finally remark, that heat diminishes magnetism, and even makes it disappear; because, on separating the atoms from each other, it breaks the electric chains which these atoms formed, or at least diminishes the intensity of the current that traverses them.*

* The recent experiments made on the dilatation of bodies, and particularly those of Magnus and Regnault, on the dilatation of gases, have effectually de-

Let us now pass on to diamagnetism. That which distinguishes diamagnetic bodies from those that are not so, is that their atoms being more distant, there cannot be established among them any natural electro-atomic chain; the atoms are, therefore, independent of each other, in an electric point of view, and are consequently in that state of equilibrium in which their exterior currents neutralise the interior current that is directed along their axis. But, if we present to the integrant molecules, composed of a greater or less number of these atoms, a closed exterior current *, this current is not able to impress upon them a particular direction, since they are not surrounded by an electro-atomic current, as the magnetic particles are; but, if it is sufficiently energetic, it determines among such of these atoms as are the nearest to it a direction such that their axis is parallel to its own direction, and that their poles are at the same time turned in a contrary direction to that of the polarised particles of the conductor of the current, in a manner analogous to that which occurs in electro-dynamic induction. These atoms, thus directed under this powerful influence, will in their turn oblige the other atoms of the molecule, of which they form a part, to direct themselves so as to correspond by their opposite poles, and thus to form an electric chain; the current of which will necessarily have a contrary direction to that of the exterior current, since this direction is determined by the first atoms that are directly subject to the action of this current. Things will happen similarly for the other particles of the diamagnetic body, providing they are surrounded — at least all that are under the exterior influence —by electric currents having a contrary direction to that of the currents that are acting upon them, and which will necessarily produce a repulsion.

The difference between a magnetic and a diamagnetic

monstrated that dilatation by heat not only consists in the separation of the integrant molecules from each one; but also in a dilatation proper of these particles themselves, and consequently, in a separation of the atoms themselves, of which they are formed.

* I understand, by action of closed exterior current, the action either of a closed voltaic current, or of an electro-magnet, or of an ordinary magnet.

body will, therefore, consist in this,—that, in the former, as the currents are pre-existing around the particles, the exterior action of a closed current has no other effect than to impress upon their particles a common direction, and such that these currents are parallel to those acting upon them, and moving in the same direction; this constitutes magnetisation; whilst in the latter, as the particles are not surrounded by a natural electro-atomic current, they do not themselves change place, but they are forced, by the arrangement which the exterior action impresses upon their atoms, to be surrounded by an electric current moving in a direction contrary to that of the currents that are acting upon them. We see that we thus arrive at the same conclusions as Weber, with regard to the difference between magnetism and diamagnetism.

In truth it is a real phenomenon of induction that occurs in the action exercised over the diamagnetic molecule, with this difference, that the induction occurs only in the molecule, and not in the whole conductor, and that it lasts as long as the inducing cause, instead of being instantaneous. Another difference is that the molecular induction occurs as well in non-conducting as in conducting bodies, whilst that which gives rise to currents of a finite size, can only be produced in conducting bodies.

The causes of these differences can easily be apprehended, when we compare the actual nature of the two phenomena. Electro-dynamic induction is the result, as we have seen, of the polarisation of the successive integrant molecules, and of the discharges of the contrary electricities of these consecutive molecules; this is a purely physical phenomenon, in which the mere nature of the particles plays no part, except in as far as their greater or less degree of electric conductibility is concerned; it is altogether analogous to the effects of the induction of static electricity, and to those of disguised electricities. Thus induction is manifested in the same manner in magnetic bodies, whose integrant molecules are surrounded by a natural electric current, and in diamagnetic bodies, in which this molecular current is induced; it is

merely necessary that the body shall be a conductor; and the intensity of the effect depends on the greater or less degree of the conductibility of the body. It is not the same with molecular induction, which is the cause of diamagnetism. Being due to a particular arrangement of the atoms of the molecules, it lasts only so long as the action exists by which this arrangement is produced. We can conceive that this action should be very energetic, in order to be able to disturb the natural arrangement of the atoms, and then to determine the continuous neutralisation of the contrary electricities of the consecutive atoms, even though they are not very near together, and are often bad conductors of electricity. All the facts agree with this mode of regarding this order of phenomena. Thus not only is electro-dynamic induction manifested in magnetic and even in magnetised bodies, as if they were not such, but it is also simultaneous with diamagnetism, and disturbs its effects, when circumstances, favourable to its production, are united.

We therefore see that, by causes of an entirely different order, diamagnetic bodies, so long as they are under the influence of closed currents, have their particles surrounded by currents having a direction contrary to those of these closed currents, whilst the particles of magnetic bodies, under this influence, have their currents determined in the same direction. This opposition very naturally explains all the differential effects that are observed, on mixing together magnetic and diamagnetic substances, and also the method of arriving at a mixture, which is indifferent to the action of the magnet. It equally explains the opposite effects observed by Weber, when he introduced into the helix, while being traversed by electric currents, sometimes a rod of iron, at other times a cylinder of bismuth; only, in all this class of phenomena, we must guard against the influence of superficial inductive currents; and for this purpose only operate with masses that are very much divided and not continuous. The experiments in which Matteucci had never succeeded in obtaining the least effect upon the magnetised needle, when passing a powerful discharge into the helix, in the centre of which was a piece of

bismuth, whilst it was merely necessary for the bismuth to be replaced by a body containing an almost inappreciable quantity of iron, in order to obtain an action, is due to diamagnetism, requiring for its development, first, a certain arrangement of atoms, and then the production of the current, which is the consequence of this arrangement, and its not being able to be produced under the influence of an instantaneous charge *; whilst magnetisation, being only the result of a direction impressed upon particles already surrounded by an electric current, may be determined instantaneously. Finally, it is easy to see that all magnetic and diamagnetic phenomena peculiar to crystals, being traceable according to the works of MM. Tyndall and Knoblauch, to those presented by an agglomeration of independent magnetic and diamagnetic plates, may be perfectly well reconciled with the theory, which explains the effects that are produced upon these plates.

With regard to the rotation of the plane of polarisation exercised by transparent diamagnetic substances, it is evidently not due to molecular electric currents, resulting from the action of exterior currents upon these substances, but to the arrangement of atoms brought about by this action. Thus the two phenomena, rotation of the plane of polarisation and diamagnetism, have not between them the dependence of cause and effect, but that of being due to the same cause, namely, a particular arrangement of the atoms in the integrant molecules, which very well accords with the observation of M. Biot, that is generally admitted, namely, that the rotation of the plane of polarisation is a phenomenon altogether molecular. We likewise perceive how the direction of the rotation must depend upon the direction of the current by which it is produced, since this direction determines the arrangement of the atoms of the particles in a certain direction, and in a direction precisely opposite, when it is itself changed. The proof that the rotation of the plane of polarisation is not due to molecular

* Mr. Faraday and M. E. Becquerel have both remarked, that a certain time (some seconds) is required for a diamagnetic body to acquire all the rotatory power of which it is susceptible.

currents is found in the fact, that magnetic liquids, in which these currents exist naturally, do not produce the phenomenon when an exterior action gives a similar direction to all the currents; or produces it in so feeble a degree, that we may conclude the effect only arises from the diamagnetic liquid (commonly water) in which the magnetic body is dissolved. It likewise appears that in magnetic substances, the atoms of which the integrant molecule is constituted, are too near together, even when their mutual polarisation imparts to them a regular arrangement, for their being able to act upon the polarised ray. It is otherwise for diamagnetic bodies, in which the exterior action, although it gives to the atoms of the molecule an arrangement analogous to that which the atoms of the magnetic molecules naturally have, cannot determine among them a similar approximation; which causes that the current resulting from the common direction impressed upon them is always very feeble, but which at the same time permits these atoms to act individually upon polarised light, and to produce the rotation of the plane of polarisation with an intensity depending at once upon their proper nature, and upon the energy of the action, by which they are directed.

This is the theory which, in the present state of science, seems to us to give the best representation of all the phenomena relating to magnetism and to the exterior action of electric currents. It seems to us to agree very well with the various observations that we have described. It is true that it does not explain the particular nature of the action of the atom upon polarised light; but it merely shows that, whatever this action may be, the magnetic influence must give to the atoms a common direction, which causes all their actions to concur, and the molecule, consequently, to act in a certain manner on the interposed ether.

We shall not terminate this subject without relating also some very recent experiments by which Mr. Tyndall has succeeded in demonstrating the existence of diamagnetic polarity. In this recent investigation, Mr. Tyndall, after having established primary characteristics of the magnetic

force, institutes a searching comparison between the phenomena of magnetic and diamagnetic bodies, in three distinct cases; first, when operated on by the magnet alone; secondly, when operated on by the current alone; and, thirdly, when operated on by the magnet and the current combined. It was found necessary, in order to avoid the gravest errors, to take strict account of the molecular structure of the bismuth used in these experiments. A bar of this substance cut, in a certain manner, from the crystallised mass exhibits, between the poles of a magnet, precisely the same visible deportment as a bar of iron; while it is well known that the normal deportment of bismuth is opposed to that of iron. The author, in his examination of the points before us, divides magnetic bodies into two distinct classes, and he classified diamagnetic bodies in a similar manner; one class he calls *normal*, and the other, a *abnormal*. A normal magnetic bar is one which sets its length from pole to pole in the magnetic field; and a normal diamagnetic bar is one which sets its length, at right angles to the line joining the poles. An abnormal magnetic bar is one which sets equatorial in the magnetic field; while an abnormal diamagnetic bar sets its length axial. In all the three cases mentioned, whether operated on by the magnet alone, by the current alone, or by the magnet and the current combined, the deportment of the normal magnetic bar is precisely antithetical to that of the normal diamagnetic bar; while the deportment of the abnormal paramagnetic bar is antithetical to that of the abnormal diamagnetic one. But the normal magnetic bar presents to the eye the same phenomena as the abnormal diamagnetic one; while the normal diamagnetic bar presents the same deportment as the abnormal magnetic one. A want of attention to the peculiarities of structure, which produce these remarkable effects, has introduced considerable error into this portion of science.

A bar of iron, surrounded by an electric current, exhibits that *twoness* of action, — those phenomena of attraction and repulsion at its two ends, to which we give the name of *polarity*. Tyndall's paper contains an account of experi-

ments made with the view of ascertaining whether similar phenomena are exhibited by a bar of bismuth; such experiments have been attempted by others without success; but, when sufficient power is combined with sufficient delicacy, the most complete mastery is obtained over the motions of the bar of bismuth. With one disposition of the forces the ends of the bar of bismuth were promptly repelled by the magnetic poles; with another arrangement they were just as promptly *attracted*. In all cases, where an iron bar was substituted for a bismuth one, a deflection precisely opposite to that of the latter was produced. The action was augmented by bringing four magnetic poles to bear simultaneously upon the suspected bismuth; the two poles, to the right of the bismuth bar, were always of the same name; while the two to the left of the bar, were of the opposite quality: with this arrangement the experiment has been repeated in the presence of many eminent men; the approach and recession of the bismuth bar, in obedience to the direction of the current around it, or the polarity of the magnets acting upon it, were rendered strikingly manifest to all. In a recent investigation, Tyndall has reversed the conditions of experiment, by making the magnet the movable body, and permitting an excited diamagnetic bar to act upon it; he has succeeded in completely establishing the result already announced by Weber, but questioned by several physicists of eminence, and has produced with insulators all the results hitherto obtained with bismuth alone. The question of diamagnetic polarity may therefore be regarded as settled in the affirmative; indeed, no proof can be brought forward in favour of the polarity of a magnetic body of the same capacity for magnetisation as bismuth, and equally devoid of coercive force, which cannot be matched, by proofs of equal value of the polarity of the diamagnetic body.*

* See, in the final note X, the title of the principal works relative to the subjects treated on in the present Appendix, as well as in the Second and Third Parts of this Treatise, which are contained in the First Volume.

PART IV.

TRANSMISSION OF ELECTRICITY.

CHAPTER I.

PROPAGATION OF ELECTRICITY.

General Notions upon the Propagation of Electricity.

AFTER having studied the general laws of electricity, both in the static and in the dynamic state, our attention is called to the more special phenomena that result from the transmission of this agent through different media.

The fundamental characteristic of these phenomena by which they are distinguished from those that have formed the subject of our study in the Second and Third Parts, is that they depend essentially upon the particular nature of the medium that is traversed by the electricity; while the former, which are independent of this, and remain the same, whatever the medium may be, constitute the general laws of electricity.

Before entering upon the examination of the varied and numerous effects that are produced in bodies by the transmission of electricity, we shall devote this First Chapter to the consideration of the transmission itself, viewed both in respect to the manner in which it takes place, and to the influence that is exercised upon it by the medium through which it is operating. Certain general notions on the propagation of electricity will serve as an introduction to this study.

The word propagation carries with it the idea of motion; and, in our opinion, electricity in motion is electricity in that state which results from the reunion or neutralisation of the two opposite electrical principles. We have seen that this reunion may be either *continuous* or *instantaneous*; that, in

the former case, it constitutes a current, in the latter, a simple discharge. A very rapid succession of discharges, sometimes called instantaneous currents, may form a continuous current just as the latter may be decomposed into a series of discontinuous currents by means of a rheotome. The characteristic of the current which sometimes exists for an instant only, and is then called *temporary*, is that it acts on the magnetic galvanometer; whilst the discharge, which is completely instantaneous, exercises no action upon this instrument, although it produces a great number of other effects. When we purpose studying the laws of propagation, we must for the most part make use of currents, except in certain exceptional cases, in which the employment of discharges may be necessary, in order to discover certain special features of the phenomenon.

The most simple manner of looking into the propagation of electricity is to consider it in a conducting body by which the two poles of a voltaic pile are united: the two electricities which are being constantly liberated at each of the two poles, neutralise each other continuously, in proportion as they are produced, through the conductor, and constitute the current, whose exterior properties or general laws we have already studied in the Third Part. As this current is propagated in the entire mass of the conductor, the direction of its propagation is determined by the mere form of the conduction; it will be rectilinear if this conductor is in a straight line; curvilinear, if in a curved line.

When the conductor has no very determinate dimensions, or is almost undefined in all directions, as, for example, an arm of the sea would be with the two poles of a pile plunged into the water at a certain distance apart, the current determinates itself in all directions, as we shall see further on; still, however, being subject to this condition, that all the infinitely minute filaments, into which it may be supposed to be subdivided, abut by their extremities upon the two poles. We perceive from this that we cannot possibly compare the propagation of electricity in a conducting medium with that of light or radiant heat; for in these two latter cases, the propa-

gation emanates from a single radiating centre, and occurs in all directions in a straight line, at least so long as the medium does not change; whilst, in the case of dynamic electricity, instead of a single one, there are two points, which may equally be considered as centres of emanation; that is to say, the two poles towards which are constantly directed, or from which as constantly emanate, the contrary electricities, whose reunion forms the current that is propagating in the surrounding medium. Moreover, M. Wartmann has demonstrated by a great number of experiments, that in its propagation dynamic electricity is susceptible of neither reflection nor refraction; and consequently that all the analogy which we might be disposed to establish between it and light or radiant heat, is completely void of foundation.

We may, however, inquire whether electricity in the static or tension state, as it is manifested on an insulated body, is not susceptible of propagating itself in the surrounding medium; in this case, we are concerned with only one electricity, either the positive or negative. We well know that an insulated and electrised body loses its electricity with greater or less rapidity, according to the state of the surrounding air, and the greater or less insulating powers of its support. Belli, and other philosophers after him, have even proved that negative electricity, under like circumstances, is dissipated more easily than positive. But the mere fact of the electric tension of the electrised body diminishing, proves that electricity propagates itself out of this body. More than this, Faraday, in his researches on static induction, has demonstrated, as we saw in the Sixth Chapter of the Second Part, that this propagation does not operate to a distance, but occurs by the intervention of bodies, even of those that are apparently the best insulators. These bodies become polarised under the influence of the electrised body; that is, that each of their particles present the two electricities separated from each other, so that, if the electrised body is positive, the negative electricities of each particle are all turned on the side of the body, and the positive on the opposite side. This is what constitutes induction. It even sometimes happens that the contrary electricities of contiguous particles neutralise each other, constituting a veri-

table transmission of electricity,—what Faraday calls *conduction*, in opposition to simple *induction*, which in his opinion always precedes conduction. It follows from this that the distinction between insulating and conducting bodies is not absolute; for even the best conductors, as we shall see hereafter, always oppose a certain resistance to the passage of electricity; and the hinderance that it suffers, although much less in degree, is of the same kind as that which is observed with even the best insulating bodies, as spermaceti, lac, or sulphur.

M. Matteucci, as the result of a great number of experiments made upon the propagation of electricity in solid insulating bodies, has confirmed and extended the results that had been obtained by Faraday. He established in all insulating bodies, but in different degrees, according to their nature, the development of the molecular electric state, of which we have been speaking; so that each molecule has the two contrary electric states developed upon its opposite faces. He has also shown that these molecular electric states may destroy each other; and consequently that the electricity may propagate itself either upon the surface or within the interior of the body. The property of insulation, therefore, consists only in the greater or less resistance opposed by bodies that are endowed with it, to the destruction of the molecular electric states, by the entry or the escape of the electric fluids from the molecules themselves; a resistance that depends upon several circumstances, due either to the nature, the dimensions, or the other physical conditions of the body, or to the intensity of the electricity with which the insulating body is charged. Hereafter, when we are engaged in a more special manner on the propagation of electricity in insulating bodies, we shall return to the facts from which M. Matteucci draws the conclusions to which we have been referring.

We may therefore admit, as we have already incidentally mentioned in the Fifth Chapter of the Third Part, p. 18, that the propagation of electricity in all cases takes place by means of the neutralisation of the opposite electricities of the particles of the body, through which the transmission is taking place,—a neutralisation that is always preceded by a mole-

cular induction, that is to say, by the separation of these electricities in each molecule. In very good conducting bodies these successive inductions and neutralisations take place with very great rapidity; in insulating bodies they take place less rapidly, and the more slowly as the body is a better insulator. It is manifest, therefore, that there is never any propagation of a single electricity; and that the only difference existing between the case in which the medium is in communication with a single electrised body, and that in which it is placed between two bodies charged with contrary electricity, is that in the latter case there is an effect double of what occurs in the former; for it is easy to see that the two effects, instead of destroying each other, must be added together. For if we suppose (*fig.* 179.) two series of molecules

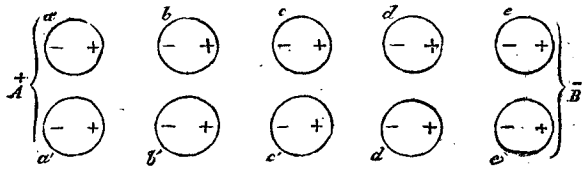

Fig. 179.

between the body A charged with positive electricity, and the body B charged with negative, the series of molecules *a*, *b*, *c*, *d*, *e*, upon which A is acting, will be polarised exactly like the series of molecules *a'*, *b'*, *c'*, *d'*, *é* upon which B is acting; but in fact the two series, or rather all the series of molecules comprised between A and B, are subjected at once to the action of A and the action of B, which must produce upon them an effect the double of what would have resulted from the sole action of A or B. This principle is equally true, whether we are concerned with a continuous current or a simple discharge.

The direction according to which the propagation occurs, when two bodies charged with contrary electricities, as the two poles of a pile, are presented to each other, is determined by the direction according to which the consecutive molecules interposed between these two bodies are placed, and through which this propagation takes place. When there is only one electrised

body, it is the ground, or rather the nearest conductor communicating with the ground, which fulfils the office of the second electrised body, as follows from the analysis that we have been making of the phenomenon. We must not in either case suppose that the particles composing the most conducting portion of the interposed medium are the only ones through which the propagation takes place; under certain circumstances, this propagation occurs through the others also. Thus, Sir. W. S. Harris has remarked that, if the discharge of a highly charged battery of Leyden jars of twenty-five square feet is passed through a fine iron wire enclosed in a receiver in which the air has been highly rarefied, the wire appears in no way affected, but the surrounding air becomes luminous, whilst, on allowing the air to enter into the receiver, the wire is immediately melted, even when a battery of only five square feet is employed. The same occurs in rarefied air, if a voltaic pile is employed instead of a battery of Leyden jars. These differences are due to there being nothing absolute in the conducting faculty of bodies, and to their depending upon different conditions, relating either to the condition of the medium or to the origin,—that is to say, the intensity of the electricity.

The decomposition and recomposition of the two electricities in each particle of the medium through which the propagation of the electricity takes place, may be accompanied by effects, either chemical, calorific luminous, or physical, according to the nature of this medium and the physiological conditions under which it exists, and according to the mode of production of the electric agent. It may also happen, in certain cases, when the medium presents a great resistance to this neutralisation of the contrary electricities of the consecutive particles, that these particles undergo a mechanical displacement, whence arises a motion in the medium if it is liquid or gaseous, and a rupture if it is solid. We shall carefully examine these different phenomena, the study of which will furnish a confirmation of the manner in which we are explaining the mode of the propagation of electricity.

After this first general glance that we have made at the

propagation of electricity, we shall in the present Chapter first investigate the laws to which it is subject in good conductors, both solid and liquid; we shall then determine the influence that is exerted upon it by the particular nature of these good conductors, and the physical conditions in which they occur. We shall then study this same propagation in solids and liquids that are insulators, or rather imperfect conductors, as well as in elastic fluids and *in vacuo*. We shall terminate the examination by the exposition of the researches that have been made on the actual velocity with which the propagation takes place. This is the object of this First Chapter.

The chemical, physical, and physiological effects, that accompany the transmission of electricity, will be the object of the following chapters.

In the study that we are about to enter upon, we shall make use of the voltameters that we have described in the First Part of this work, as well as of the magnetic galvanometers, to the description of which we have devoted the Fourth Chapter of the Third Part. We shall employ, as sources of electricity, either the electric machine, the voltaic pile, or the magneto-electric machine, which produces induction currents. These three apparatus, although each capable, as we shall presently see, of producing electricity under all forms, are nevertheless more particularly suited, the electric machine for producing it under the form of the discharge, the pile under the form of a continuous current, the magneto-electric machine under the form of a discontinuous current. On this account we shall in preference employ one or other of these three apparatus, according as we shall require electricity under one or other of these three forms. We shall be directed in our choice by the nature also of the bodies through which we shall have occasion to bring about the transmission of the electricity, and by that of the effects that we are desirous of producing.

Laws of the Propagation of Electricity in good Conductors.

We have just seen that no conductors, however good, are

absolutely perfect conductors of electricity; but that all bodies, even those which appear to conduct it best, oppose a certain resistance to its propagation. However, we shall consider as good conductors all those which permit of a tolerably rapid propagation of electricity, so that the current resulting therefrom is able to act upon the magnetised needle, and consequently to produce the general phenomena of electrodynamics. It is true that this definition has still the inconvenience of not being absolute; for the same body—pure water, for example—may be classed or not classed among good conductors, and according to the apparatus employed for producing the electricity; according to the mode of communication that is established between it and this apparatus; and, finally, according to the physical conditions under which it is placed. But this is of little importance so long as we are only concerned in determining the laws of the propagation itself: it is in the subsequent paragraph, which is devoted to the study of the conducting powers of different bodies, that we must have regard to these anomalies. It is also of little importance whether the apparatus, of which we are about to avail ourselves for the production of the electricity, be of one kind or of another. The only conditions with which it must comply, are to be sufficiently powerful to give us, with the conductor that we are about to employ, a continuous current, capable of acting directly and at will without the employment of the galvanometer upon the magnetised needle, and sufficiently constant that this current may preserve the same intensity during the continuance of the experiments. A Daniell's or a Grove's pile, of two or three pairs, as an electro-motive apparatus, wires or metal plates, and saline or acid solutions as conductors, will perfectly satisfy the required conditions.

The first law that we shall encounter, when we are studying the propagation of electricity in a conductor, is the tendency that the electric current possesses of distributing itself, or rather of being disseminated, throughout the whole extent of this conductor. This law, which I established for

solid conductors in 1824 *, and for liquids in 1825, may be easily demonstrated in various ways. In order to demonstrate it in solid conductors, we have merely to take a very wide plate of copper, one of 5 or 6 inches for instance, and about a foot in length, terminated at its extremities by two wires, also of copper, placed on the prolongation of the line that divides the plate into two equal parts, and intended for placing it in the voltaic circuit. This plate is arranged vertically within the cage of a torsion-balance, the wire of which carries an astatic conductor; and which is so placed that its different longitudinal sections are successively opposite to the vertical branch of this conductor. The current is then so directed that it shall pass in opposite directions in the plate, and in the movable conducting wire, which gives rise to a repulsion. We find, on taking the mean of many experiments, that the angles of torsion necessary to bring the movable conductor back and into contact with the fixed conductor, are sensibly the same, whatever be the portion of the latter that is acting upon it. If the current is directed so that attraction takes place, we find that the angles of torsion, necessary for detaching the movable conductor from the fixed one, are the same, whatever portion of the latter be made to act upon the other. In order to measure their force of mutual attraction or repulsion, we place the two conductors at an almost imperceptible distance from each other, so as to be sure that the action is due only to the actual section of the fixed conductor that is situated opposite to the movable conductor, the action of the other sections being exerted too obliquely to produce an appreciable effect. It follows from this experiment, that dynamic electricity appears to be equally distributed throughout the whole extent of a plate serving as its conductor, and gives rise to as many parallel currents, of equal intensity with each other, as we may suppose there are infinitely thin sections in the rectangular plate.

* *Mém. de la Soc. de Physique et de l'Histoire Nat. de Genève*, tom. iii. p. 109.; and *Ann. de Ch. et de Phys.* tom. xxviii. p. 190.

We arrive at the same result by placing horizontally, in the direction of the magnetic meridian, the copper plate, or a surface of mercury, to which we may give a width of as much as 8 or 10 inches; and by bringing as near to it as possible a very small magnetised needle, perfectly horizontal, and very delicately suspended. The deviation that occurs to this needle, when the conducting surface above which it is situate is placed on the circuit, is the same, whatever be the portion of this surface that is acting directly upon it, provided that the needle is never so near to the edge that, when it is deflected, its extremity is situated beyond the surface. Thus we are led to admit that the electric current, on entering into a solid conductor, distributes itself through the whole extent of this conductor, by small parallel filaments, all of equal intensity; whence it follows necessarily, that the less considerable this extent is, the more will the electric current be condensed, and the greater consequently will be its intensity in each section of the conductor; a result that is fully confirmed by experiment, when we employ a conducting plate of uniform thickness, but wider in a certain part of its length than in others; the action of the plate upon the needle is more intense in proportion as the portion over which the needle is placed, is narrower. This same condensation of the current is demonstrated by the power, which the narrow part of the conducting plate possesses, of attracting iron filings, whilst the wide part does not attract the slightest quantity. To the same cause also, as we shall presently see, is due the development of heat that accompanies the passage of the electric current in the narrow parts of a conductor, whose wide parts suffer no sensible change of temperature, although they are traversed by the same current during the same time.

The law, that we have just laid down, is only verified in an accurate manner in conductors in which one of the dimensions, the length, exceeds the others, which constitutes the case of linear propagation. In other cases, the law is less simple. M. Kirchoff, who made a particular study of this subject, has, however, arrived at results which are altogether in con-

formity with the theory whereby the propagation of electricity is explained.*

Dynamic electricity equally manifests this same tendency of distributing itself in a liquid conductor that is susceptible of being decomposed, as well as in a solid conductor, or a liquid such as mercury. I proved this in the following manner in 1825. Take a large trough, some 2 ft. or more in diameter, for instance, and 3 or 4 inches deep, and fill it with salt water or diluted acid, and then plunge into it the two poles of the pile, each at a distance of 2 or 3 inches from the edge, and so that they are situated on the same diameter. It is well to employ as electrodes two platinum spheres, of about half an inch, for instance, in diameter, each surmounted by a metal stem, covered with an insulating coating, serving to sustain them, and to make communication with the poles of the pile. Then attach to each of the extremities of the wire of a magnetic galvanometer a small rod of platinum, and by means of a piece of ivory or any other insulating body, maintain these two rods, which are of the same diameter and the same length, always at the same distance apart, 2 inches, for example. Then plunge this species of fork into various parts of the liquid that is traversed by the current, taking care that the extent of the portion immersed is always the same. In this way we collect the portion of the current that traversed the section of liquid interposed between the two platinum points of the galvanometer. We find that it is greatest in quantity on the right line that joins the two poles of the pile and between these poles, but that upon this line itself it increases in intensity, setting out from the middle, where it is most feeble, to near the poles, where it attains its maximum. However, we find currents in all parts of the liquid, even behind the poles, that is, in the parts comprised between each pole and the edge of the trough. The diffusion of the currents is the more decided, in proportion as the liquid is a worse conductor; so that it seems as if the currents describe, from one pole to the other, curves of greater or less curvature.

* See the final note A., for the explanation of M. Kirchoff's researches.

It would be an interesting matter to determine exactly the form of these curves, by searching, by means of platinum gauges, for all the elements of the filament that have the same intensity; which would enable us to trace out the polygon, and consequently the isodynamic curve, which would probably vary with the conductibility of the liquid.

M. Matteucci, who published in 1839 some researches on the same subject, adopted also the same method, but employing as gauges plates instead of wires of platinum. The chief object of his experiments was to determine the influence which the extent and distance of the immersed plates exercise over the intensity of the current that they are able to absorb; and he found, that in proportion as the liquid is a better conductor, so must their surface and their mutual distance be increased in order to collect a current of the same force. And if the immersed surfaces of the plates are equal, their distance, in a saturated solution of sulphate of copper, must be twenty times greater than in distilled water. When the two poles are not in the line that divides the liquid mass in the middle, it is found that the current absorbed by the gauges, at an equal distance from the middle line, but on the two different sides of this line, is always more powerful on the side that is nearer the edge of the trough, namely, in the stratum that contains the less liquid. I should add, that M. Matteucci made his experiments, by employing a double galvanometer, and two perfectly similar systems of gauges, so arranged that the current collected by one was led in a contrary direction to that collected by the other. Hence it followed, that whenever the two collected currents were perfectly equal, the needle of the galvanometer remained at rest; and that the direction of its deviation, when it occurred, indicated which of the two currents was the more intense.

The second law, to which the propagation of electricity in a conductor is subject, is, that two or more electric currents may be propagated in the same conductor without mutually modifying each other, and consequently in a manner altogether independent of each other. M. Marianini has proved this property by passing through a liquid, placed in a cubical

vessel, two currents, so arranged that the filaments of which they are composed cross each other at right angles, without any variation occurring in the intensity of either of them; an intensity which remains the same whether they pass separately or both together through the liquid conducting mass. A third current may be also transmitted through the same liquid that is already transmitting the other two, and in a direction perpendicular to them; and this transmission operates in the same manner as if this liquid were not traversed by any current. This independence in the propagation of currents has been also established by passing two or even three currents through a column of liquid, in directions more or less oblique to each other, and even by transmitting them through the wire of the same galvanometer, upon which the effect observed is always the sum or the difference of the individual effects of the partial currents.

These facts, at first sight, seem to establish a great analogy between dynamic electricity and light, the rays of which may all cross each other in the same small hole without undergoing the least alteration, and each preserving its own character and its special properties. However, the analogy is more apparent than real; for, as we have remarked in the preceding section, the propagation of electricity cannot be assimilated to a radiation, and in fact it possesses none of its properties, not having of itself a rectilinear direction, nor being capable of undergoing reflection, refraction, or polarisation.

A third law, which at the first glance seems also to be favourable to the analogy that we have just rejected, is the diminution of intensity that electricity undergoes in its propagation through a liquid mass, when it is intercepted on its route by metal plates or diaphragms interposed in the liquid. This phenomenon, which, I pointed out in 1825, is easily demonstrated by separating with metal plates, into two or more distinct compartments, a conducting mass of liquid contained in a rectangular vessel 10 or 12 inches long, into the two extremities of which the poles of a pile are inserted. A galvanometer, placed in the circuit of the transmitted current,

indicates, by the amplitude of its deviations, that this current suffers a sensible diminution of intensity, by the interposition of one or more metal diaphragms, even when the diaphragm is a better conductor than the liquid section that it replaces. But this diminution is proportionately less for the same diaphragm, as the number of diaphragms already interposed is greater, and as the number of pairs constituting the pile employed is greater. Thus a current, which by the interposition of two diaphragms is not more than 75° is reduced to 73° only, by the interposition of a third; whereas a current of an initial intensity of 75° is reduced to 67° by the interposition of a single diaphragm. M. Marianini and other philosophers, who have made a great number of experiments on this subject, have all confirmed my conclusions. This influence of diaphragms is also rendered evident by calorific and chemical voltameters, as well as by the magnetic galvanometer. Thus, a current, which when transmitted through nitric acid marks 38° on the calorific galvanometer placed in its circuit, gives only 30° when a platinum diaphragm divides the column of nitric acid into two compartments, and 0° when there are two diaphragms instead of one. The first diaphragm, which reduces the calorific effect to the $\frac{1}{15}$th of what it was originally, reduces the chemical effect only to $\frac{1}{8}$th. In fact, with the chemical voltameter placed in the circuit of the current, instead of the calorific we find that it requires 5′ for the liberation of a certain quantity of gas, when there is no diaphragm, whilst it requires 25′ if there is one diaphragm.

It is well known that light and radiant heat undergo a diminution of intensity, which is subject to the same laws, when we interpose in their course one or more diaphragms that are more or less capable of transmitting them under their radiant form; this had given rise to the analogy to which we referred just now. Here also the analogy is in fact more apparent than real; for it is easy to prove that the phenomenon of diaphragms, in the case of electricity, is only a phenomenon of conductibility. I had noticed, as far back as 1825, that so long as the metal diaphragm does not entirely prevent the two portions of liquid that it separates from communicating

together, the current deviates in great part from its route, rather than traverse the diaphragm. M. Matteucci obtained a still more significant result, by placing within a large trough filled with a conducting liquid a box about $\frac{3}{4}$in. wide and 4in. long, closed at its two ends by two platinum plates, whilst its two longer sides were of wood. After having filled it with the same conducting liquid, and to the same level, he places it so that its two platinum faces were in front of the poles of the pile, which were placed in the large trough. One of the two systems of gauges is plunged inside the box, and the other outside; but both are placed symmetrically in respect to the line, that joins the two poles. When the deviation of the galvanometer which is in favour of the system exterior to the box, has become constant, the interior system is to be taken away; and this makes no change whatever in the deviation; a proof that no current was transmitted in the liquid withinside the box, and that the current instead of traversing the two plates, is inflected round the sides, so as to pass only through the continuous portion of the liquid.

Independently, however, of the resistance proper, opposed by a liquid and a solid to the transmission of an electric current, there is a special resistance due to the mere fact of the passage of the current from a solid into a liquid, or from a liquid into a solid. We call this resistance, the *resistance to passage.* It always takes place while a liquid is being traversed by an electric current; for, in order to put this liquid into the circuit, solid conductors, called electrodes, must necessarily be employed. This resistance to passage does not appear, as several philosophers have supposed, to be the effect of a peculiar property appertaining to the very nature of the electric current, as is the case in respect of the action of screens upon light, and upon radiant heat. It is rather the result of the electro-chemical phenomena which, in virtue of the decomposing action of the current, necessarily occur on the surfaces of the solid conductors that are in contact with the liquids in which they are transmitting this current. These very complex phenomena, which we shall study hereafter, must depend

upon the chemical nature of the solid and liquid conductors that are in contact, and upon the various circumstances by which their mutual action may be modified. And in reference to this, I had already remarked in 1825, that the resistance to passage is less, in proportion as the liquid exercises a more powerful chemical action upon the solid conductor; and I observed subsequently, that the elevation of the temperature of the electrodes, more particularly of the negative electrode, also diminishes it. I had also succeeded in completely annihilating it, by employing currents passing alternately in a contrary direction, as those which are obtained with a magneto-electric machine, or by simply placing a commutator or rheotrope in the circuit of an ordinary voltaic current. In this case, for example, the currents that alternately succeed each other, produce upon the solid surfaces chemical effects that are alternately contrary, and consequently which neutralise each other; and then, by taking certain precautions,—such as employing tolerably energetic currents, and causing them to succeed each other with great rapidity, —we succeed, as we have just mentioned, in annihilating the resistance to passage. In the Chapter wherein we shall be engaged with the electro-chemical decomposition of bodies, we shall return to this class of phenomena, which immediately depend upon it.

A fourth law, that regulates the propagation of electricity, is, that all the successive parts of a closed circuit, including also the apparatus itself which produces the electric current, are traversed at the same time by the same quantity of electricity, whatever be the diversity of their nature, their form, and their extent; circumstances, which influence only the absolute quantity of electricity that is in circulation, and not its relative intensity in different parts of the circuit. Also, if we have in the same circuit, first the pile, then a wire coming from one of its poles and entering into a liquid, and two or more parallel wires extending from this liquid to the other pole, the quantity of electricity that, under the form of a current, traverses the pile itself, the first wire, the liquid, and the two or more parallel wires, is exactly the

same. It is clear that, if this latter system of conductors is composed of two wires, and these two wires are perfectly similar in all respects, the quantity of electricity that circulates in each of them is the half of what is circulating in the first wire; it would be the third if there were three wires, and so on; but in the two or three united, it is together the same as in the first wire. Ampère had obtained a glimpse of this important law, when he showed that the effect produced upon the magnetised needle is the same whatever be the portion of a voltaic circuit, including the pile, that acts upon it. M. Becquerel had proved it in a more accurate manner, by soldering wires at different points, taken at equal distances, on a metal conductor that connects the two poles of a pile, which wires he connected with the ends of a galvanometer, and finding that the currents conducted by these wires two by two were equal in force, when the portions of the principal conductor, intercepted by the two systems of soldered wire were themselves equal.

I have myself on several occasions announced the same principle, founding it upon facts that I shall set forth in the Chapter of the Fifth Part in which I shall be treating of the theory of the voltaic pile. Finally, Pouillet and Fechner have demonstrated this law in a direct manner. M. Pouillet placed all the successive elements of a thermo-electric pile in the magnetic meridian, as he did also the conductor employed for the completion of the circuit; and he found that a magnetised needle placed above any part of the whole circuit always obtained the same deviation, whatever this part was. M. Fechner on his part obtained a similar result by making a magnetised needle oscillate over the different solid portions of a voltaic circuit, placed perpendicularly to the direction of the needle, and discovering that these oscillations are executed in the same time, which proves the equality of the intensity of the current in these different parts. However, he did not verify by direct experiment, that this equality extends to the liquid conductors of the pile, which is however generally admitted.

The law to which we are referring, admitted implicitly by

Ohm in his theory of the pile, has been proved less by direct experiments, than by the consequences that have been derived from it, and which have always been verified. It appears to me, however, to be necessary to give it a positive experimental demonstration. The following is the description of the apparatus that I have constructed for this purpose. (*Fig.* 180.)

The ends of glass tubes which are all of the same diameter,

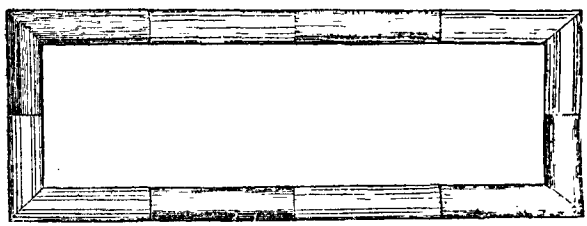

Fig. 180.

and perfectly symmetrical throughout, are united to each other by solid or hollow metal cylinders of the same exterior diameter as the tubes, and presenting a face of zinc at one of their extremities and a face of copper at the other. The glass tubes are filled with different conducting liquids; and the circuit is completed by means of a glass tube, also of the same diameter as the others, and filled with mercury. We thus obtain a circuit composed of voltaic pairs, of liquids, of hollow and of solid metal conductors, and of a column of mercury; in a word, of parts that are all conductors, although some only of them are active; and the transverse section is the same to all. If the different parts of this circuit are successively arranged so that they are parallel to the magnetic meridian, a magnetised needle, delicately suspended over each of them, executes the same number of oscillations; the needle does not suffer any deviation, when it is placed exactly between two opposite parts of this circuit, each parallel to the meridian. These results prove that the sum of the electric forces, that are traversing at the same time each of the transverse sections of this circuit, is absolutely the same. We have merely to substitute for the liquid in one of the

compartments, another liquid that is a worse or a better conductor, and we diminish or increase the absolute intensity of the current, not only in the part of the circuit that is modified, but equally in the whole of the circuit; so that its force remains always the same in all portions at the same instant.

In the preceding experiment, I have supposed that the circuit, although heterogeneous, is however such that all its transverse sections are equal. The law equally holds good, when they are unequal. To prove this, we have merely to supply the place of the mercury that is in the tube, by a wire of any diameter, either homogeneous or composed of pieces of different metals soldered end to end, taking care to put the wire in the axis of the same tube which was previously occupied by the mercury, and in such a manner that it also completes the circuit. If the magnetised needle is placed above the different parts of this wire, it will be found to give the same number of oscillations as when it is placed over the different liquid or solid conductors that are in the rest of the circuit. Only, in order to neutralise the differences that might arise from the diversity of diameters of the different parts of the circuit, we must take the precaution of so placing the needle, that it may not be too near, but always in such a position that it is everywhere at the same distance from the axis of the conductors that are acting upon it.

It follows from this fourth law, that the absolute intensity of the electricity, that travels in the form of a current through a closed circuit, depends upon two circumstances alone,—the force or forces that produce the electricity, and which we may call electro-motive forces, and the resistances to conductibility presented by all the circuit taken together. This latter element, which had never previously been taken into account, was pointed out by myself, both in 1825, in the memoir to which I have already alluded above and also in the subsequent researches that I published in 1828 and afterwards. In an important work which appeared in 1827, M. Ohm, as a result of purely theoretical speculations, came to the conclusion that the force of the current in a closed circuit is directly proportional to the sum of the electro-

motive forces that are in activity in the circuit, and which we will call E, and inversely proportional to the total resistance, or the sum of the resistances of all the parts of the circuit, which we will designate by R; in other words, that the intensity of the current, I, is equal to the sum of the electro-motive forces, divided by the sum of the resistances: $I = \frac{E}{R}$. Experiment has proved the accuracy of this formula, within limits sufficient for the purposes, to which we are required to apply it in the present chapter. We shall return to this in the sequel, when we are engaged upon the theory of the pile.

A fifth law, which arises immediately out of the preceding, is, that if we increase or diminish the resistance of any part of a circuit, the total intensity of the current diminishes or increases, all other circumstances remaining the same, in a proportion, which is the same as that existing between the resistance added or removed, and the total new resistance of the entire circuit.

If in the formula, $I = \frac{E}{R}$, R becomes $R + r$, or $R - r$, I becomes $\frac{E}{R + r}$ or $\frac{E}{R - r}$. Calling I' the intensity in the former case, and I'' the intensity in the latter, we have $I : I' : I'' = \frac{E}{R} : \frac{E}{R + r} : \frac{E}{R - r} = \frac{1}{R} : \frac{1}{R + r} : \frac{1}{R - r}$; whence we deduce, $I - I' : I = r : R + r$, and $I'' - I : I = r : R - r$; namely, that the diminution of intensity is to the primitive intensity as the added resistance, r, is to the new total resistance $R + r$; and the increase $I'' - I$ is to the primitive intensity, as the suppressed resistance r is to the new total resistance $R - r$.

Fechner verified experimentally, by means of the oscillations made by the needle under the action of the magnet, the accuracy of the law that we have just stated. He hence concluded that a pile whose electro-motive force is represented by 1, and whose poles are connected by a conductor whose resistance is also equal to 1, and in which 9 represents

the resistance of the pile itself, would have a force represented by $\frac{1}{9+1}=\frac{1}{10}$. By doubling the resistance of the conductor, it is evident that we do not render the force of the pile one-half less; for it becomes $\frac{1}{9+1+1}=\frac{1}{11}$, in place of $\frac{1}{10}$, as it was at first. If it is the resistance of the conductor interposed between the poles, that is 9 times that of the pile, then by doubling this resistance, the force of the pile, which was at first equal to $\frac{1}{1+9}=\frac{1}{10}$, becomes $\frac{1}{1+18}=\frac{1}{19}$. From this we can readily perceive that, the greater the resistance of the interposed conductor, the less is the influence of the resistance of the other parts of the circuit. M. Pouillet arrived at the same verification by employing the tangent galvanometer, and by means of the following experiments. He took a single pair of Daniell's constant pile, the current from which he passed through this tangent galvanometer (*fig.* 182.), by means of two copper rods; then, with silk-covered copper wire, he made series of different lengths, of 5, 10, 40, 70, and 100 metres, which he rolled up and covered, wrapping them in a ribbon, so that the two ends, being bent back into a hook, might easily be plunged into cups of mercury, arranged for establishing communication. The following is then the mode of proceeding:—The current is passed direct through the tangent galvanometer, and the deviation is observed; then all the wires of the series are successively introduced into the circuit, the corresponding deviations being carefully noted, bearing in mind that the intensities of the successive currents are proportional to the tangents of the angles of deviation obtained. The resistance of the total circuit (which is composed of the resistances of the pair before the wires were introduced, of the wire of the galvanometer, and of the various conductors employed for establishing the communication), being R, this resistance becomes successively, in proportion as the wires of different lengths are introduced, $R + 5^m$, $R + 10^m$, &c.

The following table was obtained from these experiments: —

Resistances.	Deviations observed.	Tangents of the Deviations.
R	62°·00	1·880
R + 5^m	40°.20	0·849
R + 10^m	28°·30	0·543
R + 40^m	9°·45	0·172
R + 70^m	6°·00	0·105
R + 100^m	4°·15	0·074

By comparing the first observation with each of the others, we deduce for R the values $4^m·11$; $4^m·06$; $4^m·01$; $4^m·14$; and $4^m·09$; the mean of which is $4^m·08$. For this purpose we make use of the formula $I-I' : I = r : R+r$, putting in place of I, the value 1·880; and in place of I′ the successive values 0·849, 0·543., &c., and in the place of r, the corresponding values 5^m, 10^m, 40^m, &c.

This result shows that, with some very trifling differences, which can only be attributed to small errors of experiment, we obtain the same value for R, whichever of the subsequent observations is compared with the first; a proof that we were right in our statement, that $I-I' : I = r : R+r$; for, by substituting for I the number 1·880, we obtain for R the same value, when we put successively for r, 5^m, 10^m, 40^m, 70^m, and 100^m; and for I′, the corresponding values 0·849, 0·543, 0·172, 0·105, and 0·074. Thus the law, which gave us the formula, is quite true, since it leads, on being applied in all possible cases, to a same value for a quantity which is indeed necessarily the same.

The value of $R = 4^m·08$, indicates that the resistance of all the primitive circuit, not including consequently the copper wires that are added to it, is equal to the resistance that would be offered by a length of the same copper wire equal to $4^m·08$; this is called the *reduced length*. Thus the reduced length of a circuit is *the length of a wire, of a given nature and thickness, whose resistance is equal to the sum of the resistances of this circuit*. It is a very convenient mode of expressing the resistance to conductibility, presented by the whole or by a

part of a circuit, to reduce it to that which would be presented by a certain length of wire of a given nature and diameter. We shall see presently the advantage that has been taken of this principle, for the construction of a very valuable apparatus, intended for measuring electric currents.

But before coming to this, we have yet to establish two important laws, which follow implicitly from the preceding, but which may be demonstrated directly; these laws are, that the resistance opposed to a current by any conductor is proportional to its length and the inverse of its section. We have implicitly admitted the first of these two laws in respect to a wire, when we represented by their respective lengths the resistances added by the interposition of each of the wires of 5^m, 10^m, 40^m, 70^m, and 100^m, all having the same diameter, and being of the same nature. Now the result to which we have arrived by this hypothesis, when applied to many different experiments, having, as we have seen, always been in accordance with the facts, we may regard it as a truth. However, our formula rested upon another hypothesis, which it was intended also to verify,—namely, the existence of the fifth law, in respect to the relation between the variations of intensity of the current and the variations of resistance. Is the accordance of this single formula with facts sufficient to demonstrate, at the same time, both the law which has served for establishing it, and also that which has been admitted in the interpretation of the experiments? We might doubt this, if there were but one single experiment; but since there are a great number, and all lead to the same result, we must hence conclude that the supposition which has been made, of the proportionality between the length of a conductor and the resistance that it opposes to the current, is very exact.

The second law relative to section may be verified by a series of experiments, similar to those which have served us for obtaining the laws relating to lengths, by putting successively into the circuit wires of the same nature and the same length, but of different diameters, and by determining in each case the value of the total resistance, or rather that of the diminution or the increase that this resistance experiences by

the substitution of wires of diameters differing from each other.

Davy, Becquerel, Harris, Cumming, and generally all philosophers who have directed their attention to the conductibility of bodies for electricity, have commenced by proving that *the conducting power of a wire is in inverse ratio of the length, and in direct ratio of the section of the wire,* — a law which amounts to precisely the same as the one we have just given. We shall make known the various processes of these philosophers in the part of this Chapter which is devoted to the determination of the conducting power of different bodies, and to the study of the causes, by which it may be modified.

Between the two laws, that we have just laid down, there is an important difference. The first, namely, the one relating to lengths, requires being proved directly by experiment; the second, that of sections, is a consequence of the uniform distribution of electricity in motion in all parts of a homogeneous conductor. Indeed, this distribution, which shows us that dynamic electricity does not tend, like static electricity, to the surface of bodies, but diffuses itself throughout their whole interiors, leads us to recognise, since it is uniform in a homogeneous conducting mass, that electric conductibility must increase, and consequently resistance must diminish, with the number of points, or rather with the size or the extent of the section made in the conductors. The only condition is, that the conductor must necessarily be homogeneous in the transverse direction; for if it were not so, the distribution of electricity would no longer be uniform, and the law could evidently no longer be maintained.

The law of lengths and sections is not only applicable to solid conductors, but is equally so to liquids. Only it is more difficult of demonstration in the latter case than in the former, because, in order to put the liquid into the circuit, metal electrodes must be employed; and, as we have seen, by the mere fact of the passage of the current from the solid into the liquid, and from the liquid into the solid, there is a diminution of intensity, which is completely independent

of the conductibility proper of the liquid itself. However, we may eliminate the effect of this element by employing a liquid column, that may be elongated or shortened without making any change in the electrodes. A tube, closed at one of its ends by a disc of platinum, serving as one of the electrodes, and in which a piston moves, whose platinum base serves as the other electrode, answers the purpose well; for, when once the tube is full of liquid, we are able, by moving the piston onward, either to elongate or to shorten the portion of the liquid column that is included in the circuit. We shall describe this apparatus more in detail, when engaged on the conductibility of liquids.

Fechner, in his great work, of which we have already spoken, had determined the law by which the resistance of the conductor is connected with its length, as well in the case of a liquid as of a solid conductor. He found, always by the method of oscillations, that the addition of equal lengths of wire increases the resistance by equal quantities; and he hence concluded, that the resistance of wires is proportional to their lengths. He afterwards arrived at the same law for the liquid conductor, by successively separating the plates of the pairs of the pile by a quantity always the same; and he thus found that the resistance of liquids is proportional to the thickness of the liquid stratum, that the current has to traverse. This law is equally true, whether the section of the liquid is equal to the surface of the plates of the electrodes, or whether it is greater. With regard to the law that connects the resistance of the liquid with the size of its section, Fechner found that it is verified only so long as the surface of the electrode is equal to that of the section. Thus, if we place vertically in a trough two metal plates, serving as electrodes, and pour into the trough an increasing proportion of a conducting liquid, the total resistance diminishes by quantities corresponding with the quantity of liquid that is added. But when once the extension of the liquid has passed, by a certain degree, the size of the surface of metal that is immersed, an increase in the section of the liquid no longer diminishes sensibly the resistance; at least,

this is what Fechner believes. We shall see further on, when occupied with the conductibility of the terrestrial globe, that this opinion is true, but that the limit at which an increase of the section ceases to exercise any influence over the resistance or the conductibility of a body, depends upon a great many circumstances, and especially upon the intensity itself of the electricity in motion.

Finally, a last important law, which is equally the result of the preceding and also confirmed by experiment, is that which regulates the distribution of the electric current between two parallel conductors placed in the circuit. If they are of the same nature, of the same diameter, and of the same length, — a condition which is realised for instance by two similar wires, — it is evident that the current divides itself equally between them. But if they are of different lengths, still being of the same nature and the same diameter, let the length of one be m, and that of the other n, then the proportion of the current that traverses each of them is inversely as its length, and the total intensity of the current is the same as if, instead of the two wires of the lengths m and n, a single wire were placed in the circuit of a length $\frac{m\,n}{m+n}$.* Generally, if a and b represent the respective resistances of any two conductors interposed parallelly in the circuit, the complete resistance of the two conductors is the same as that of a single conductor the resistance of which might be expressed by $\frac{a\,b}{a+b}$. The two conductors may differ in their nature, their length, and their section, or in these three circumstances together.

* In fact, from the law of lengths, by letting i' and i'' represent the intensities of two partial currents, passing respectively by the wires of the length m and the length n, $i' + i''$ being equal to i, the intensity of the total current, we obtain $i' : i'' = n : m$; whence $i' + i''$, or $i : i' = n + m : n$; whence

$$\frac{i'}{i' + i''} = \frac{n}{n + m}$$

We obtain also, $i' + i''$ or $i : i'' = m : x$; x being the length sought for; whence

$$x = \frac{i'}{i' + i''} \times m = \frac{n}{n+m} \times m = \frac{m\,n}{m+n}.$$

Only it is necessary that they be both metallic or both liquid; for if one is metallic and the other liquid, the law is not verified, on account of the new element arising out of the resistance to passage. The following experiment of Poggendorff's makes evident this important exception to the law. In the axis of a vertical glass tube, he inserted a platinum wire 80·5 in. in length, the resistance of which was the same as that of 86 in. of German silver wire. He filled this tube with diluted sulphuric acid, containing 10 per cent. of concentrated acid; and he found that the resistance of this liquid column, when placed alone in the circuit, was the same as that of 10 in. of German silver wire; and consequently at least $8\frac{1}{2}$ times less than that of the platinum wire. By means of a very sensitive galvanometer, capable of detecting a difference of $\frac{1}{8}$th of a line in the length of the platinum wire, or of the liquid column, he proved that the resistance of the platinum wire, as determined when it was alone in the tube, is not diminished when this tube is filled with the conducting liquid; a proof that no portion of the current passes through the liquid, and that consequently, although the latter is a much better conductor than the wire, no division of the current takes place between it and the wire, which would have occurred between two metals and even between two liquid conductors. We may in like manner prove that there is no diffusion of current from the metal to the liquid, by arranging the platinum wire through a horizontal vessel filled with an acid solution, and by plunging into the solution, very near to the wire, two platinum plates in communication with the extremities of a very sensitive galvanometer. If the current is then passed through the platinum wire, not the slightest effect is obtained upon the galvanometer.

The law that we have last set forth, leads us to say a few words upon derived currents, to which we shall frequently have occasion to direct our attention, the theory of which is a consequence of this law. When, in a closed circuit, we connect two points of this circuit by an additional conductor, we bring about what is called a *derivation* of the

current. The two points of the circuit, from one of which the new conductor is led out, and to the other of which it returns, are termed *points of derivation;* and the interval by which they are separated, *the distance of derivation;* the conductor, or added wire, is the *derivation wire;* the portion of the current that passes by this wire is termed the *derived current;* that which continues to pass by the part of the circuit, comprised between the two points of derivation, *partial current;* and, finally, we designate by the name of *primitive current* the current as it existed before the derivation was made; and of *principal current,* the whole of the new current necessarily more powerful, that traverses the entire circuit, when the *derivation* wire has been added.

From the principles we have laid down, and the laws we have traced out, it is easy to determine the intensities of the principal current, of the derived current, and of the partial current, if we know that of the primitive current, the reduced length of the primitive circuit, the distance of the points of derivation, and the conductibility or the resistance of the derivation wire. We shall defer to the Note B. at the end, the determination of these intensities, as well as the description of the processes by means of which different philosophers, and Wheatstone especially, have applied the laws that regulate the properties of derived currents to the construction of apparatus and instruments suitable for determining with great precision, in a multitude of cases, the intensity of electric forces.* We shall confine ourselves in this place to describing the apparatus of Wheatstone's that is most frequently employed. This is the *Rheostat.* It is founded upon one of the laws, that we have already laid down, namely, that the resistance to conductibility of an homogeneous wire is proportional to its length.

The object to be accomplished by this apparatus of Wheatstone's is, to introduce into the circuit of the current, whose intensity we are desirous of measuring, a wire the interposition of which produces a known resistance; then to vary the length of this wire, by a quantity that may be measured

* *Vide* Note B. at the end.

with great accuracy, and without making any change in the rest of the circuit, so as to produce a resistance which shall cause the current to come back to a given intensity that is always the same. This operation being performed upon different currents, gives immediately the relations existing between their relative intensities. The great advantage it presents is, that it enables us to bring back always to the same degree the indications of the galvanometer that is placed in the circuit, by making the resistance vary; which does away with the necessity of our knowing the relations that exist between the deviation of the galvanometer needle and the intensity of the corresponding current, which relations cannot easily be determined, and never exactly. We have only to admit the self-evident principle, that every time we obtain the same deviation with the same galvanometer, it indicates that the intensity of the currents producing this deviation is the same.

Jacobi and Poggendorff had also each of them contrived an apparatus analogous to Wheatstone's, founded on the same principle, and accomplishing the same object. In Poggendorff's apparatus, the wire, whose length was made to vary, is of German silver; in Jacobi's, which is termed by its inventor *Volta-agometer*, it is of platinum. In Wheatstone's, the wire is of copper or of brass. These apparatus differ from each other in respect to the details of their construction: we shall confine ourselves to a description of Wheatstone's, the employment of which appears to us more convenient and more generally known. The author has constructed two upon the same principle; one for circuits in which the resistance is considerable, the other for those in which it is feeble.

The former instrument (*fig.* 181.) is at A; *g* is a cylinder of wood, *h* a cylinder of brass, both of the same diameters, and having their axes parallel. On the wooden cylinder a spiral groove is cut; and at one of its extremities a brass ring is fixed, to which is attached one of the ends of a long wire of very small diameter. When this wire is coiled round the wooden cylinder, it fills the entire groove; it is fixed by its other end to the opposite extremity of the brass

cylinder. Two springs *j* and *k*, pressing, one against the brass ring of the wooden cylinder, and the other against the extremity of the brass cylinder *h*, may be connected by means of two binding screws with the wires of the circuit. The movable handle *m* is for turning the cylinders on their axes. When

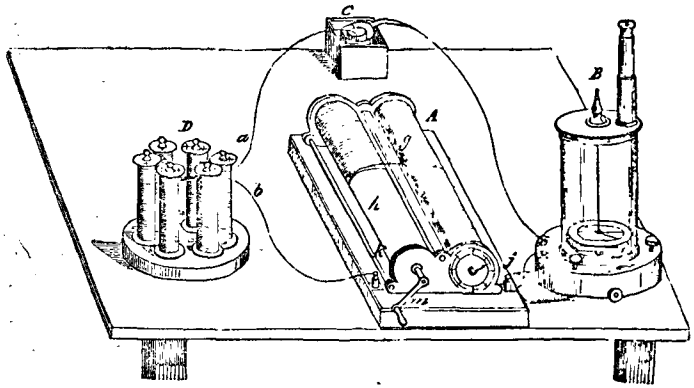

Fig. 181.

it is fitted on the cylinder *h*, and turned from left to right, the wire is uncoiled from the wooden cylinder, and coiled upon the brass cylinder; but when it is fitted to the cylinder *g*, and is turned from right to left, the reverse takes place. The convolutions upon the wooden cylinder being insulated and kept separate from each other by the groove, the current passes the entire length of wire coiled upon that cylinder; but the convolutions upon the brass cylinder not being insulated, the current passes immediately from the point of wire in contact with the cylinder to the spring *k*. The effective part of the length of wire is reduced, therefore, to the variable portion coiled around the wooden cylinder. In the instrument commonly employed by Mr. Wheatstone, the cylinders are 6 inches in length by $1\frac{1}{2}$ inch in diameter, the threads of the screw are forty to an inch, and the wire, which is of brass, is $\frac{1}{100}$th of an inch in diameter. The wire, as may be perceived, is very fine and a very bad conductor, so that we are thus enabled to introduce a greater resistance into the circuit. A scale measures the number of convolutions wound off, and

divides the fractions of convolutions by means of an index, fixed to the axis of one of the cylinders, which traverse the divisions of a graduated circle. It follows from this, that we are able to determine the exact length of the portion of wire that is introduced into the circuit, as well as the value of the variations that are made in this length. *Fig.* 181. shows the arrangement of the apparatus, when it is in use for an experiment. B is a very sensitive galvanometer with an astatic needle, carrying a microscope for reading off the divisions of the circle, which greatly facilitates the observations. C is a voltaic pair, whose electro-motive force is to be measured. D are bobbins of wire covered with silk, of which one or more are introduced into the circuit in order to increase the resistance. We shall see in the Fifth Part, which is devoted to the study of the sources of electricity, how easily by means of the rheostat we may arrive at the determination of electro-motive forces.*

The rheostat A (*fig.* 182.), which is intended for circuits

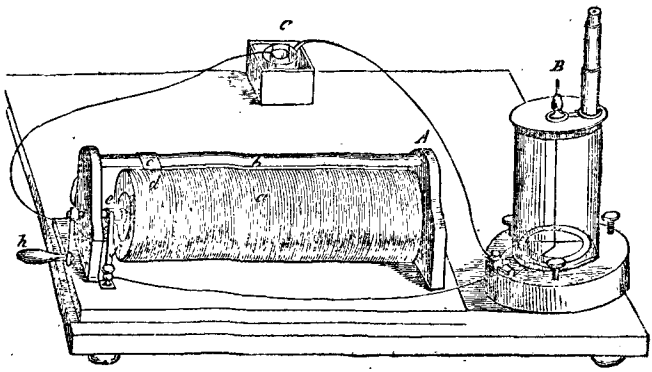

Fig. 182.

wherein the resistance is comparatively feeble, is a cylinder, *a*, of very dry wood, upon the surface of which a helical groove is cut; a thick copper wire is wound round the cylinder, filling the groove and forming as it were the thread of

* M. Rumkorff is now constructing, in Paris, rheostats in which a grooved glass cylinder is used in place of the wooden one, and which affords much more security in the employment of the instrument.

a screw. Immediately over the cylinder, and parallel with its axis, is placed a triangular bar of metal, *b*, carrying a rider, *c*; to this rider is attached a spring, *d*, which is constantly pressing against the spirals of the copper wire, yielding to all the little inequalities. One end of the metallic helix is attached to a brass ring, *e*, against which passes a spring that is in communication, by means of a connecting screw, with one end of the circuit; the other end of the circuit is retained by a similar screw, which is also in metallic connection with the triangular bar of metal. On turning the handle, *b*, the cylinder is rotated on its axis, in either one or other direction, and the rider, *c*, guided by the copper wire, slides along the bar, advancing or receding according as the cylinder rotates to the right or to the left. As the rider comes in contact with a different point of the copper wire, a different resistance is introduced into the circuit, consisting of that portion alone of the wire which is comprised between the rider and the end that is in communication with the spring. The cylinder of the instrument constructed by Mr. Wheatstone is $10\frac{1}{2}$ inches in length, and $3\frac{1}{4}$ inches in diameter. The wire is of copper $\frac{1}{16}$th of an inch in diameter; it makes 108 coils round the cylinder. The dimensions of the instrument, as well as that of the wire, may be modified according to the limits of the variable resistance that we propose introducing into the circuit, and according to the degree of accuracy with which we purpose measuring these variations.

We must not quit this subject without adding that M. Jacobi, who has deeply studied the means of measuring electric currents, has proposed to philosophers to reduce the instrument wherewith they are in the habit of measuring resistances to the same unit, which should be the resistance of a copper wire 1 mètre (3·28 ft.) in length, and 1 millimètre (·039 in.) in diameter; but as all coppers are not identical, it would be necessary to choose arbitrarily any wire, and send it from one philosopher to another. M. Jacobi has already endeavoured to realise this. Perhaps the best method would be to employ mercury as the standard of resistance for the construction of rheostats, or agometers, as M. Jacobi calls them.

Mercury in fact has the advantage of being able, by means of distillation, to be reduced to a state of great purity, and consequently to be always identical with itself; on account of its being liquid, it has not, like wire, the inconvenience of possessing a variable molecular structure. The only further precaution — and this is by no means difficult — is to give it constantly the same dimensions. M. Jacobi has moreover himself already constructed an agometer with mercury; and he appears to have succeeded in measuring resistances, by means of this apparatus, with a precision which permits of the probable error being diminished to the hundred thousandth part of the total resistance.

Electric Conductibility of Solids and Liquids.

We have seen that there is no perfect conductor, but that all bodies present a greater or less resistance to the propagation of electricity. We have considered, as possessing what we call electric conductibility, those bodies which afford to electricity a propagation sufficiently rapid to give rise to the dynamic condition, as detected by the action upon the magnetised needle. Thus, while resistance to the propagation of electricity would be a general property of bodies, conductibility, as we understand it, would belong to only a certain number among them. This is not saying that all substances, even the most insulating, are unable to transmit more or less electricity; but it requires for those that we call insulators, such as glass, the resins, gutta-percha, oils, atmospheric air, an electric source of a very great intensity. And even with the most energetic source — a flash of lightning, for example — these substances do not transmit electricity under the form which constitutes what we have termed the dynamic state; but they propagate it either too slowly to act upon the magnetised needle, or too instantaneously, by themselves breaking under the action of the discharge, for a current, properly so called, to occur.

The research that must for the present engage our attention is confined merely to bodies possessed of electric conducti-

bility, such as we have been defining it. This conductibility, which, as we have seen, is never absolute, varies, as we have demonstrated, with the dimensions of bodies; but it varies also with their nature, and with different physical circumstances. These are the influences that we desire to examine, and even to measure, so as to give as accurate a Table as possible of the relative degrees of conductibility of different substances, both solid and liquid, as well as the variations that occur in their conducting powers from changes in their physical constitution, and especially in their temperature.

The determination of the specific conductibility of different bodies is not a problem easy of solution. Its solution depends upon very delicate principles, and requires apparatus possessed at once of a great sensibility and of extreme precision. In order to arrive at its solution, it would be necessary to have a constant source of electricity, so that the tension of the two electricities should remain in it constantly the same, and also to have an accurate means of measuring the quantity of electricity that is circulating in the dynamic state, in a given time, through any conductor. Then, in order to establish a comparison, we should endeavour to obtain the quantity of electricity that traverses in the unit of time an infinitely thin section of each body; and we should divide it by the surface of the section, which would give the quantity of electricity that traverses in the unit of time the unit of surface.

The principle of this method is altogether the same as that upon which the process employed for the determination of conductibility for heat is founded. Now, if we study closely what takes place during the propagation of electricity through a conducting body, we find this assimilation perfectly legitimate, as is proved by the recent experiments of Kohlrausch, which we will give briefly.

The poles of a constant voltaic pair, such as a Daniell's pair, are connected by a very fine and tolerably long wire, which is bent in zigzag, so that the sides of the angles formed by the zigzags shall be all of the same length. A point, a, of the conducting wire is placed in communication with

the ground; and then a point, b, of the wire, taken at a certain distance from a, on the side of the positive pole, is put into communication with a sensitive condenser; and after this a point, b', taken at the same distance from a, but on the side of the negative pole. The same tension is obtained; only that of the point b is positive, and that of the point b', negative: the two tensions go on increasing in proportion as the points b and b' are taken further from a.

If the two poles are united by two wires of the same nature (silver for instance), of the same length, but of different diameters, and soldered end to end so as to form only one continuous wire, the electric tension increases in each of the wires in the same progression, setting out from their point of contact, which is made to communicate with the ground; only the absolute tensions in each of the wires are the inverse of the sections. When, instead of two wires of the same nature, we take two of different natures, but of the same diameter,—for instance, one wire of *German silver*, and one of *copper*,—so that the former presents a great resistance to the current, and the latter a much less, it is found that the absolute intensities at the ends of each wire are proportional to their respective resistances, as determined by means of the rheostat, which we have described in the preceding paragraph.

The same results are obtained on making use of a liquid conductor. A trough full of sulphate of copper, in which a plate of copper is immersed, contains a porous cell, filled with sulphate of zinc, with a plate of zinc immersed. The two plates are connected by a wire. The trough is divided into equal parts; and we plunge into the liquid, in different places, two copper wires, the one communicating with the earth, and the other with the upper plate of the condenser. We find, as we had done with the metallic conductor, on either side of the point that is in communication with the earth, equal positive and negative tensions. We may even prove in this case (which we are unable to do with a solid conductor), that the tension is the same in all points of the transverse section; which

confirms the law, that we have laid down in the preceding paragraph, of the uniform distribution of dynamic electricity throughout the whole mass of a homogeneous conductor. It is necessary in these experiments, that the wires which are employed for sounding be covered along their whole length, except at their very end, with a varnish of gum-lac, so as to take the electricity only at the actual point with which this extremity is in contact. It follows, therefore, from these experiments that, even in the best conductors, the resistance to the propagation of electricity is of such magnitude that, between two consecutive transverse sections, there is a difference of electric tension, the stratum nearest to the electric source having a higher tension than that which is more distant. It is this corresponding difference for different conductors, at the same distance between two strata taken in each, that Ohm calls the electric fall; and the preceding experiments show that this fall is directly proportional to the specific resistance of the metals and inversely to their sections.

We may even by means of these laws, and with a simple calculation, determine the electroscopic state of each point of a circuit. Let e, for example, be the electro-motive force put into play in the circuit, l the reduced length of the circuit, and l' the reduced length also of the conductor that separates a point a, of the circuit from the point, where the electro-motive force is acting; we obtain e' the electroscopic state of the point a, equal to, $\frac{l'}{l}e$; which signifies that, in order to obtain the tension of a point, we must multiply the electro-motive force by the relation that exists between the reduced length of the part of the circuit confined between the point in question and the point connected with the ground, and the reduced length of the entire circuit. Experiment completely verifies this formula, as M. Kohlrausch has further proved, by uniting the zinc and copper plates of the last experiment by a long and very fine wire, bent into a zigzag. He has determined the electric tension of the different points of this wire and of the solution of sulphate

of copper which in this, as in the preceding case, formed part of the circuit. The negative pole communicated with the ground; and the different points touched were, first, three points taken on the conjunctive wire at increasing distances from the zinc plate or negative pole, then the point of contact of the copper plate with the conjunctive wire, then three points taken in the sulphate of copper, at 2·02, at 4·02, and at 8 inches from the same copper plate. The following is a Table of the calculated and the observed tensions, placed opposite to the respective values of the resistances or the reduced lengths, determined by the rheostat for the parts of the circuit comprised between the negative pole and the point that is touched:

Points touched.	Tensions calculated.	Tensions observed.
l.		
a. 118·5	0·93	0·85
b. 237	1·86	1·85
c. 355·5	2·89	2·69
d. 474	3·73	3·70
e. 610·3	4·80	5·03
f. 745·3	5·86	5·99
g. 879	6·90	6·93
h. 1014	7·98	7·96

We may therefore consider each transverse layer of an homogeneous conductor as charged with different quantities of electricity on its two faces, but spread uniformly on each of them; quantities which, for a constant electro-motive source, differ in proportion as the resistance of the layer to the propagation of electricity is greater. The determination of this difference for layers of the same extent, belonging to conductors of a different nature, would give the measure of their resistance, and consequently of their electric conductibility. But this process, which is very difficult of application, would not, after all, be susceptible of very rigorous accuracy. However, the analysis by which we have been led to it enables us to employ for it another process that is more practical and more delicate, which we will explain presently.

If we compare the results that we have just obtained, with the considerations that we have laid down, both at the commencement of this chapter, as well as previously, on the manner in which the propagation of electricity is brought about, by the polarisation of consecutive particles, we may conclude from this that the resistance to conductibility is nothing more than the sum of the resistances opposed by the successive particles to their electric polarisation, and to the neutralisation of their contrary electricities. Each particle or physical molecule possesses, as it were, a greater or less coercitive or insulating force, which opposes the separation of the two electricities from each other. Then, when this separation has been brought about, there exists a resistance to the reunion of the contrary electricities of two consecutive particles, either on account of their greater or less mutual distance, or on account of the greater or less constraining power of their very nature. Now, in order to there being propagation of electricity, it is necessary that the resistance to separation and the resistance to reunion be equally surmounted. The former depends on the very nature of the particles; the latter depends both on their nature and on their mode of aggregation. It is by taking account at the same time of these two very different elements, that we are able to explain that the same exterior circumstance — for example, the elevation of temperature — may in certain cases favour, and in other cases diminish, conductibility, according as it acts upon the particles themselves, or upon their relative positions. The electric state of the particles of a slender filament may be compared with that of a succession of Leyden jars, or rather of spangled panes, which all become charged mutually by induction, except the first and the last, which are respectively in direct communication with a source of positive and with a source of negative electricity. Having arrived at a certain degree of tension, the opposite coatings of the consecutive jars or panes discharge upon each other. There arises from this a general discharge of a uniform intensity throughout the system, and an excess of electricity upon each jar or pane, which increases onward to the extreme panes; an excess that is positive for those

which are on the side of the positive source, and negative for those which are turned on the side of the negative source. The intensity of this excess must depend upon the greater or less degree of resistance that the contrary electricities of the opposite armatures find presented to their reunion; and the more considerable it is, the less powerful is the discharge or the current. This succession of charges and discharges, which, in a series of Leyden jars, requires a certain time for bringing it about, occurs instantaneously in a series of particles; and this it is which causes the current to be continuous, and the state of tension of the different molecules to be constant, conformably with the observations of M. Kohlrausch.

It is probable that the effects of heat, of light, and of the physiological shocks that almost always attend upon the transmission of dynamic electricity, except in the cases where the resistance is very feeble, are intimately connected with the two causes of resistance, that we have pointed out. With regard to chemical decompositions, they must depend essentially upon the arrangement that the polarisation of the particles brings about, in the mode of grouping of the atoms of which they are composed, and in the disturbances that the discharges, which follow polarisation, introduce into this arrangement.

We ought to mention, that the manner in which we have been regarding electric conductibility differs notably from Mr. Faraday's mode of viewing it; who, setting out from the principle that the space by which the particles of bodies are separated is not a conductor, because, if it were otherwise, space being everywhere identical, all bodies ought equally to be conductors, deduced from it a conclusion, that is contrary to the atomic theory. In fact, regarding continuity as an essential condition of electric conductibility, and consequently considering as indispensable that intermolecular space is a conductor, since it is the only continuous part of a body, he had concluded that the atomic theory is false, because it leads us to admit at the same time that this space must be a conductor and that it must not be one. For our part, it is to

the molecule alone that we attribute the property of being more or less conducteous or insulating; conductibility is nothing more than the result of the greater or less facility possessed by the consecutive particles of polarising each other through the space by which they are separated, and which is necessarily insulating. We are thus enabled to reconcile, in the most satisfactory manner, the phenomena of electric conductibility with the atomic theory, which is so firmly established by the study of chemical and physical phenomena.

After these preliminary notions, which have appeared to us indispensable for enabling us to acquire a just idea of electric conductibility, we will pass on to the description of the processes most fitted for determining accurately the conducting power of different solid and liquid bodies.

Priestley, and after him Harris and Riess, have proposed to determine the conducting power of the different metals, by making the same electric discharge pass through rods or wires of the same diameter and the same length, but of different natures, and deducing their relative conductibility from the greater or less degree of increase in temperature that they underwent. Wilkinson adopted the same method, but by substituting an electric current for the discharge. This mode of determination depends upon the principle that the degree of increase of temperature communicated to a wire by the passage of a given quantity of electricity is inversely as its electric conductibility,—a principle which cannot be admitted *à priori;* for it cannot be proved until we have a direct means of determining conductibility; and, consequently, it cannot be employed for the determination of it.

The same objection is applicable to Christie's method, founded upon the principle that the intensity of induction currents is proportional, all other circumstances remaining the same, to the conducting power of the substance, that is the subject of the induction. Faraday had, in fact, remarked, at the very outset of his discovery of induction, that induced currents developed in helices made with wires of the same diameter and the same length, but of different natures, have

an intensity that is greater in proportion as the conducting power of the wires is greater. But here, again, in the employment of this method for determining conductibility, we have a vicious circle, which prevents our employing it for this purpose.

Davy made use of a more direct method, which led him to results that have been in great part confirmed by more exact methods. He took wires of different metals, of the same length and of the same diameter, and examined the power that was possessed by each of them for discharging voltaic pairs. In order to prove whether a wire entirely discharged several pairs, he added two other silver wires to the two poles of the pile, and made them plunge into conducting water, which was decomposed, if all the current did not pass by the principal wire; the absence of all liberation of gas was the sign that this wire brought about the entire discharge. However, in virtue of its tendency to distribution, the current must always in a certain proportion pass through the water; too small, it is true, to cause the decomposition to be sensible. Notwithstanding the imperfections of this process, Davy had succeeded in establishing directly the two general laws of conductibility, namely, that conducting powers are in inverse ratio to the lengths, and in direct ratio to the sections of the wires, that conduct the electricity.

M. Becquerel, sen., was the first to adopt a more accurate process; which consists in employing the differential galvanometer, and which enabled him to guard against the effects of variations in the intensity of the electric current. He obliged the current to divide itself between the two wires of the galvanometer in such a manner, that each of its two portions travelled in an inverse direction, and maintained the magnetised needle at zero, when they were equal. By introducing into these two partial circuits wires of different natures, and of the same diameter, he was always able, by shortening or by lengthening them, to bring back the needle to zero, and thus to determine what lengths of the wires were equivalent in conductibility. In this manner he had also verified the

laws that Davy had already found approximately, and had determined the relative conductive powers of different metals.

M. Pouillet had more recently adopted an analogous method, with this difference, that he employed two perfectly equal sources of electricity, the currents of which passed in contrary directions in the two wires of the differential galvanometer; a platinum wire served as the standard wire; with the conducting power of which he compared that of the wire under examination, giving to it such a length as reduced its current as much as the interposition of the experimental wire reduced the current that was compelled to traverse it.

The numerical results obtained by M. Pouillet, with regard to the conducting powers of the different metals, do not agree with those of M. Becquerel, which may be traceable to certain differences in molecular constitution, and in the degree of purity of the specimens submitted to experiment,—circumstances, which exercise a great influence over electric conductibility, as was demonstrated by M. E. Becquerel, who has lately taken up this question, and applied much accuracy to its study.

He also employed the differential galvanometer; but he took care to introduce into its construction the precaution pointed out by Poggendorff of twisting the two galvanometer wires around each other, in order that, if the two equal currents pass in an inverse direction in the instrument, their action shall be entirely the same, and that the needle may remain perfectly at zero. M. E. Becquerel also made use of Wheatstone's rheostat, the wire of which, and to which the desired length can be given, forms constantly part of one of the circuits of the differential galvanometer, whilst the wire, whose conducting power is in question, forms part of the other. The toothed wheel of the rheostat contains 108 divisions, and the tenth part of each division can be estimated; so that the circumference of one of the spirals of the helix, being 9·27 in., the lengthening or shortening of the brass wire of the instrument may be measured to the $\frac{1}{1080}$ part of 9·27 in., or to about ·008 in. The wire whose conducting power is the

subject of inquiry is stretched between two clips of copper, attached to two standards, placed at such a distance apart, that the length of the wire is 4·92 feet. A very solid copper rod is firmly fixed above the wire, and parallel to its length; upon this rod, which is graduated, a copper standard slides tightly, which by the aid of a screw may be fixed in any given position. The upper extremity of this standard is formed of a thick clip, which holds the wire in one of its points; so that, on causing the standard to traverse along the rod, any length is placed in the circuit, and is measured with great accuracy. The conductibility of the rod, in respect to that of the wire, may be neglected, in consequence of its great dimensions. The form of the apparatus, complete, is given in *fig.* 183. H H′ is the differential galvanometer; F F′ the voltaic pair employed in the experiment; E E′ the rheostat, with its handle M, by which motion is communicated to the two cylinders, one being of copper, and the other of wood, so that the wire is wound around one, while it is unwound from the other; R R′ the two standards carrying the clips A A′, between which the experimental wire is strained; *a b* the divided copper

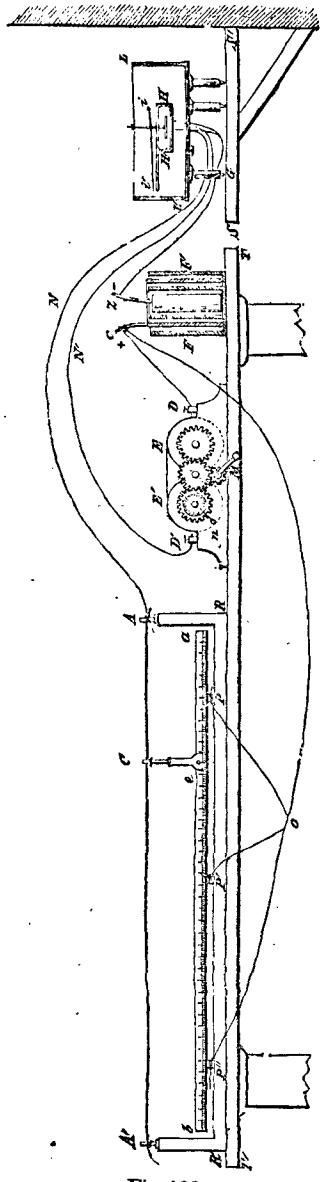

Fig. 183.

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rod; and *e* C the metal standard, which slides firmly along this rod, so as to place the length C A of the experimental wire in one of the partial circuits. The current, setting out from *c*, divides between the two conductors *c* D and *c* O, so that the first part passes through the wire of the rheostat D D′, and thence goes on by the conductor D′ N′ to traverse one of the wires of the galvanometer; the second part goes through the conductors *o* P, *o* P′, *o* P″, to arrive hence by the standard *e* C at the experimental wire E A, and then to travel, by means of A N, to the second wire of the galvanometer; then the two currents, after having traversed in contrary directions the two wires of the differential galvanometer, unite at G, and find there the conductor G *z*, which completes the circuit.

M. E. Becquerel first verified, by means of this apparatus, the law already indicated,—that the conducting power is in inverse ratio to the length, and in direct ratio to the section of the wire.

A First Table contains experiments made at the temperature of 60° with an iron wire 0·012 in. in diameter, and of variable length. The first column indicates, by the position of the clip C *e*, the variable lengths of the wire; the second, the number of divisions of the rheostat which present resistances equal to those of the corresponding lengths of the iron wires; the third, the relation between these two quantities. Now, this relation being constant, it follows that the resistance, brought about by the introduction of the iron wire into the circuit, increases just proportionately to the length of this wire; or, which comes to the same thing, that its conductibility is inversely as its length.

The following is the table: —

Position of the clip C *e*, on the divided rule or the length of the iron wire.	Divisions of the toothed wheel, or length of the standard wire.	Relation between the corresponding lengths of the two wires.
0 Cent.		
20	162·6	8·13
40	325·2	8·13
60	485·0	8·08
80	643·3	8·04
100	805·6	8·06

A Second Table contains the experiments made with two iron wires of different diameters. For one metre of length a resistance is obtained, which is represented in the following Table:—

Resistance in divisions of the rheostat.	Diameters of the wire.	Squares of the diameters.	Product of the squares of the diameters by the resistances.
157·08	0·7370	0·5322	85·717
928·65	0·3037	0·0922	85·622

Thus, the increase of resistance, caused by the introduction into the circuit of an iron wire of a certain length, is to that produced by the introduction of a wire of the same length, but of a different diameter, inversely as the squares of the two diameters.

After these preliminary experiments come those which are made with wires of different metals, the diameters of which must be very accurately measured. But since some wires, when they come out of the drawplate, are hardened, but not all, and since hardening influences conductibility, as M. Pouillet has observed, it is of importance to anneal them, in order that all may be as much as possible in the same molecular conditions. The difference in respect to conductibility, between an annealed wire and the same wire unannealed is really very sensible, as may be seen by the following Table: —

Wires of the diameter of 0,mm 3.	Resistances unannealed.	Resistances annealed.	Conducting powers unannealed.	Conducting powers annealed.	Relation of conductibility of annealed and unannealed metal.
Pure silver	123·509	115·416	93·448	100·000	1·0701
Pure copper	119·559	126·222	89·084	91·439	1·0264
Pure gold -	179·260	176·320	64·385	65·458	1·0166
Iron - -	951·098	942·046	12·124	12·246	1·0101
Platina -	1435·158	1416·007	8·042	8·147	1·0130

We should mention, that in this Table the resistance, and consequently the conductibility of the wires, is reduced to what it would be by supposing them all to be of the same

diameter; we have also compared all the conductibilities with that of annealed silver, which is the best conductor of all

Temperature, as well as hardening, influences in a notable manner the conductibility of metals. In order to study this influence, M. Becquerel winds the wire that is to be experimented upon, around a glass tube in such a manner, that the spirals of the helix which it forms are well insulated from each other; he then attaches the two ends to two great studs of copper, whose very good conductibility does not sensibly vary, in respect to that of the wire itself, under the influence of the temperature to which it is exposed. He places the tube mounted with its wire in an oil-bath, which he gradually raises from 0° to 100° (32° to 257° Fah.), and which he in like manner cools down from 100° to 0°; he then determines the variations of conductibility of the wire by means of the rheostat. This variation follows in a very regular manner in the same metal that of the temperature, to which it is in general proportional; but it differs much from one metal to the other, and is not in relation with its absolute conductibility. We may discover this from the following Table, which contains the relative conducting powers of different metals at 0° and at 100°. The order is much the same, except for lead and platinum, which change places; but the numerical relations, which indicate their relative conductibility are notably altered, except for copper, cadmium, and zinc.

Substances.	Conducting powers at 0°.	Conducting powers at 100°, compared with silver at 0°.	Relation of conducting powers at 100°.
Pure silver, annealed	100	71·316	100
Pure copper, annealed	91·519	64·919	91·30
Pure gold, annealed	64·960	48·489	67·992
Cadmium - -	24·579	17·506	24·547
Zinc - - -	24·063	17·596	24·673
Tin - - -	14·014	8·657	12·139
Iron, annealed -	12·350	8·587	11·760
Lead - - -	8·277	5·764	8·078
Platinum, annealed	7·933	6·688	9·378
Mercury - -	1·7387	1·5749	2·2083

It is unfortunate that M. E. Becquerel has not investigated the influence of elevation of temperature upon metals above 100°. Happily M. Lenz has determined this as high as 200° (480° Fah.) The following is the table of the results that he obtained:—

	At 0°	At 100°	At 200°
Silver	136·25	94·45	68·72
Copper	100·00	73·00	54·82
Gold	79·79	65·20	54·49
Tin	30·84	20·44	14·78
Brass	29·33	24·78	21·45
Iron	17·74	10·87	7·00
Lead	14·62	9·61	6·76
Platinum	14·16	10·93	9·00

This Table, the numerical elements of which differ but little from that of M. Becquerel, confirms the remark that we have already made with regard to the influence exercised by temperature, not only over the absolute conductibility, but also over the relative conductibility of metals. Thus we see the conducting power of gold, which at 0° is only $\frac{4}{5}$ of that of copper, becomes equal to it at 200°; brass, which at 0° is inferior to tin, becomes superior to it at 100°, and still more so at 200°; finally, platinum, which at 0° is inferior to lead and iron, becomes superior to them at 100° and at 200°: the most fusible and evidently the metals that vary most rapidly in the scale of conductibility under the influence of an elevated temperature; a proof of the influence of molecular constitution over this property of bodies.

Besides the solid substances that we have mentioned, there are some others whose conducting power has been determined. Still calling the conducting power of copper 100°, Lenz found

Antimony	8·9
Mercury	4·7
Bismuth	2·6;

but he does not point out the influence of elevation of temperature upon the conductibility of these metals.

Palladium is one of the metals, concerning which the experiments of various philosophers have given the least concordant results. Thus, whilst Pouillet found that it is the best conductor of all the metals, E. Becquerel and Riess place it after silver, copper, gold, cadmium, zinc, and tin. These divergences are probably due to certain differences in the degree of purity of the specimens submitted to experiment.

The electric conductibility of carbon has never been determined with precision. This is due to the differences that it presents, from diamond, which is completely insulating, to graphite and plumbago, which conduct very well. Mr. Kemp has pointed out the very great influence of elevation of temperature over the conducting power of wood carbon, which it increases considerably. But this influence, which is the reverse of that exercised over metal, differs also from it in its being permanent; that is to say, that it is the fact of having been exposed to a very high temperature which renders wood carbon a better conductor. Thus, M. Violette, in his recent researches on wood carbons, found that fragments of the carbon of elder wood, prepared at the temperature of 1500°, are better and more equable conductors than the graphite that is taken out of gas retorts. We shall, however, return to this subject when we are describing the voltaic arc, that is obtained with two carbon points.

The conductibility of metals for electricity as we said at the beginning, is a phenomenon that is intimately related to their conductibility for heat. We have a direct proof of this in the fact observed by Prof. Forbes as much as twenty years ago, that the order of the conductibility of metals is the same for heat as for electricity. The following Table was drawn out by MM. Wiedemann and Franz, as the result of fresh researches that were made by them upon the conducting power of metals for heat, which gives evidence of this relationship in a remarkable manner.

Names of metals.	Conductibility for electricity.			Conductibility for heat.
	Riess.	Becquerel.	Lenz.	
Silver - -	100	100	100	100
Copper - -	66·7	91·5	73·3	73·6
Gold - - -	59·0	64·9	58·5	53·2
Brass - - -	18·4	„	21·5	23·6
Tin - - -	10·0	14·0	22·6	14·5
Iron - - -	12·0	12·35	13·0	11·9
Lead - -	7·0	8·27	10·7	8·5
Platinum - -	10·5	7·93	10·3	6·4
German silver -	5·9	„	„	6·3
Bismuth - -	„	„	1·9	1·8

Finally, there exists a great number of mineral substances which are able to transmit an electric current, but whose rank or numerical co-efficient of conductibility we have not been able to determine. MM. Henrici and Hanemann, on the one hand, and M. Wartman on the other, have made numerous experiments on this subject. The latter philosopher examined 319 species of minerals; 252 of which he found to be insulators, and consequently only 67 conductors. The difficulty of reducing these substances to the same dimensions, and even of giving to them geometric volumes susceptible of being exactly estimated, renders it an impossibility to determine their relations of conductibility, still less the variations of conductibility which may be manifested in the same mineral, for example, according as the electricity is propagated in one direction or the other. Moreover, there is nothing absolute in the conducting property; for between all the minerals, that are the best conductors and those which are the best insulators, there are all the intermediate degrees. We shall prove this further on, in the paragraph in which we shall be engaged upon the propagation of electricity in bodies that are bad conductors.

The determination of the conducting power of liquids has been obtained by following the same process as for solids; we have merely to pay regard to two circumstances, which do not occur when operating upon solids. The first is the resistance to passage, that occurs in the transmission of the

electric current at the surface of contact of the liquid and the metal electrodes,—a resistance altogether independent of the electric conductibility properly so called of the liquid; the second is the alteration that very rapidly occurs to the liquid that is submitted to experiment, in consequence of the chemical decomposition which it undergoes. In order to obviate this latter inconvenience, it is necessary to operate as rapidly as possible, and to arrange the apparatus in such a manner that the substances liberated by decomposition do not alter the liquid. With this view, we endeavour to absorb them, if they are gaseous, by the substance itself of the electrodes, when it is possible, as with oxygen; or to allow them to deposit, if they are solid, in the portion of the liquid which is at the bottom of the vessel, and which we take care not to include in the circuit.

It is a more difficult matter to obviate the former inconvenience. For this purpose, M. E. Becquerel adopts a process which is merely a modification of that proposed by Mr. Wheatstone, and which we have employed in order to prove that with liquids, as well as with solids, the resistance to conductibility is proportional to the length of the conducting column. But, instead of a single tube, M. E. Becquerel employs two, so that he may employ the differential galvanometer, as he had done with solids; and in each of these tubes are two platinum electrodes, one fixed and the other movable like a piston, which permits of the column of liquid being lengthened or shortened at pleasure.

The apparatus is represented in *fig.* 184. A B and A′ B′ are two test glasses with feet, about $1\frac{1}{2}$ in. or 2 in. in diameter and 11 in. in height. They rest in holes countersunk in a very level base-board M N. Into these glasses descend two cylindrical tubes *a b*, *a′ b′*, supported above by corks, and retained at $1\frac{1}{2}$ in. from the bottom of these same glasses; they have the same axes with the glasses. These tubes are exactly ·846 in. in interior diameter, measured by the weight of a column of water of a certain height. In these tubes, which are placed vertically, circular plates of platinum E E′ are able to be moved upwards and downwards; they

are horizontal, and of a somewhat smaller diameter than that of these tubes, and attached to platinum wires soldered

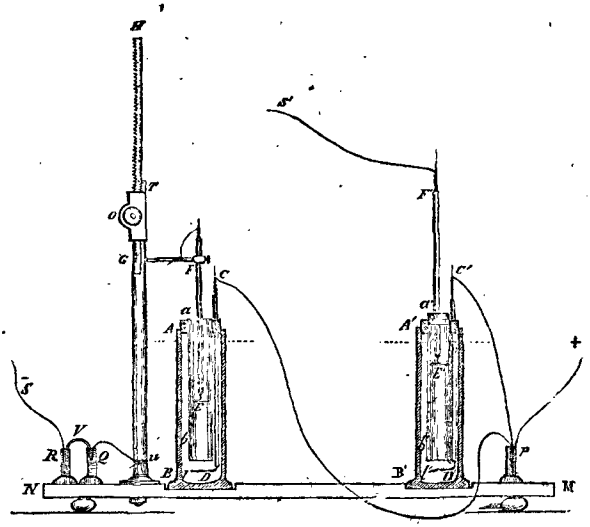


Fig. 184.

into glass tubes F E, F′ E′. Plates of different metals, D *l*, D′ *l*′, according to the experiments, are placed horizontally at the bottom of the glasses, at the lower part of the tubes *a b*, *a*′ *b*′. These plates are attached to wires of the same metal, which pass into tubes D C, D′ C′. The tube E F is attached to a stem G F, communicating with a rack-work, so that the disc E may be raised or lowered by means of this rack-work; and we are enabled by means of the vernier T to learn to about $\frac{1}{250}$ in. or even less, the amount of variation in the position of E in the tube. The other similar plate E′ is raised or lowered by means of the tube F′ E′, which passes tightly in the cork A′.

These arrangements being made, if we place the liquid by means of which we propose operating in the glasses, and send a current between the plate E and the plate D L, by raising or lowering E, we shall introduce into or withdraw from the circuit a column of liquid having the same diameter as the tube *a b*, and having for length the elevation or

lowering of the plate. The liquid comprised between the glass and the interior tube is not in the circuit. We have thus arranged the apparatus in such a manner that the products formed around the positive plate fall to the bottom of the glass, and do not alter the conductibility of the liquid that is placed within the tube *a b*. The wires C D, C′ D′ are to be connected together by being plunged into a cup *p*, filled with mercury; and by this means they are put in communication with the positive pole of one or more pairs. The negative pole is attached to the point G, at the junction of the two ends of the galvanometer wire. The two other ends N and N′ of these same wires are attached to the extremities S, S′, which are in communication with the circular plates E, E′; N is directly attached; N′ communicates by means of two cups R, Q, and by the copper U G F of the rack-work. We therefore perceive that the two circuits P C′ E′ F′ S′, P C E F S, in which are the two liquid columns E′ D′, E D, takes the place of the circuits F′ O C A N, F′ E′ N′, of *fig.* 183., which are all metal. If therefore we pass a current from one, two, four, or more pairs, similar to the pair F F′, of *fig.* 183. the current will divide between the two circuits, the plates E, E′ being at the top of the tubes; the needle of the galvanometer will be deflected a little to the right or to the left, for the two circuits are not at the first trial identical in conductibility; then, by means of the rack-work O Π, E is raised or lowered until the needle is brought back to zero. Generally speaking, except under particular circumstances, which will be referred to hereafter, it will remain there; so that by raising or lowering E 1 ^{mm} ($\frac{1}{25}$ in.), the needle is deflected to the right or to the left of zero. When once the zero is attained, the two circuits are identical in conductibility; the copper wire V, that makes communication between the cups G and R, is taken away. And in its place are substituted helices of platinum or of copper wire of a known length; the needle of the galvanometer is immediately driven in a direction which indicates that the circuit P C E F S presents a resistance greater in proportion to the wire that is substituted in place of V.

If we then lower the plate E, with the rack-work O, the needle will return to zero; and when it shall have arrived at that point, and is maintained there, we must notice how far the plate has descended. Then the length of a column of liquid, having for its diameter that of the tube *a b*, and for its length the course of the plate E, will be equal in resistance to the wire placed between R and Q, in the place of V. This resistance will be independent of the resistance to the passage from liquids into solids; for the sections are identical in the two experiments, as in Wheatstone's apparatus, and the currents are reduced to an equality. Only in this case we make the variation in the height of the liquid column employed, in order to find the value in resistance of the helix placed on V; and this is the converse of Wheatstone's process. It is necessary to employ several helices, according to the liquids that are made use of.

If the liquid under examination contains a metallic salt that is decomposed by the current, it is then in most cases essential to employ for the lower positives plates D L, D′ L′, plates of the same nature as the metal in solution; for the salt that is decomposed by the current is formed again at the positive pole. If this metal cannot be obtained in plates, an oxidisable metal must be taken; the salt that is formed remaining at the bottom of the vessel, does not enter into the tube *a b*, and in the course of the experiment does not derange the measure of the conducting power. We must, then, take care that no liberation of gas occurs upon D L and D′ L′. Since the metal deposites upon E and E′, there is no counter current, and the needle of the galvanometer is retained at zero; so that we obtain the resistance with great precision.

If a liquid is employed that is not a solution of a metallic salt, we must in this case always employ as positive plates oxidisable metals, in order to obviate the liberation of gas at the bottom of the glass; and must operate with the most feeble current that we can possibly employ, so that very little gas may be liberated at E and E′: these plates are a little en-

closed, so that the hydrogen shall not remain adhering; but, notwithstanding these precautions, the needle of the galvanometer is not fixed at zero, it oscillates a little to the right and left; and we take the position wherein the oscillations on each side have the same amplitude. However, under these circumstances the error does not exceed $\frac{1}{300}$ in the length of the liquid column. In all cases we must repeat this operation many times, in order to be sure that we arrive at the same numbers.

M. Becquerel's experiments were at first directed to the influence exercised upon the conductibility of different saline solutions by the greater or less quantity of water, that is contained in them; thus, on making use of a helix containing 9·84 feet of platinum wire, he operated upon three solutions of sulphate of copper, and at a temperature of 9°·25 (52·8 Fah.), the one saturated, the second containing $\frac{1}{2}$ the third $\frac{1}{4}$ of sulphate in volume.

The following Table gives the lengths of liquid columns for each solution equivalent to 9·84 feet of platinum wire, which enables us to deduce their conducting powers, that of silver being 100,000,000.

Solutions.	Sulphate of copper contained.	Length of liquid columns.	Conducting powers.
Saturated - -	1	3·75 in.	5·42
Diluted, so that its volume is double	$\frac{1}{2}$	2·41	3·47
Diluted, so that its volume is quadruple - -	$\frac{1}{4}$	1·44	2·08

M. Pouillet had found by Mr. Wheatstone's method a result for sulphate of copper very near to that of M. Becquerel. He had obtained for this salt a conducting power sixteen million of times more feeble than that of copper. Now, the conducting power of copper being $\frac{9}{100}$ that of silver, we see that the number 5·42 obtained by Becquerel is very near to that of M. Pouillet.

Similar experiments were made by M. E. Becquerel

upon bichloride of copper, nitrate of copper, chloride of sodium, and sulphate of zinc at different degrees of concentration. He has remarked that in some salts, such as nitrate of copper, and sulphate of zinc, the conducting power increases in proportion as the solution is diluted up to a certain limit, at which it attains a maximum; it then diminishes again, so that we can obtain a very dilute solution, that has the same conducting power as a very concentrated solution. About twenty-five years ago I made the same observation in respect to sulphuric acid, which is a better conductor when mixed with a certain proportion of water than when more concentrated or more diluted; and what is very remarkable is, that the best conducting solution of sulphuric acid is precisely that which exerts the most active chemical action upon oxidisable metals, such as zinc, iron, &c. &c.

M. Matteucci arrived at a similar result by means of a process that we will describe at the end of this paragraph, when relating other experiments of the same philosopher. The following is the Table of the conducting powers of sulphuric acid in different states of density, taking as unity the conducting power of this acid at the density of 1·259.

Densities of the acid.	Conducting powers.
1·030	0·301
1·066	0·682
1·100	0·760
1·143	0·935
1·259	1·000
1·340	0·951
1·384	0·850
1·482	0·622
1·667	0·344

Nitric and hydrochloric acids have also each of them a maximum of conductibility at a certain state of density; thus, according to M. Matteucci, nitric acid at 1·315 of density conducts better than that which has a greater or less degree of density. Hydrochloric acid at a density of 1·186 does not conduct so well as at 1·162; and conducts

better at 1·114 than at 1·076. However, with these two acids the effects are less decided than with sulphuric acid.

There is therefore an evident relation between the electric conductibility of liquids and their chemical properties. This is a point to which we shall return when occupied with the electro-chemical decomposition of liquids. The following, however, is a tolerably accurate Table of the conducting powers of certain liquids: —

Substances.	Densities.	Temperature.	Conducting powers.
Pure silver - - -	„	0°·00	100,000,000
Water saturated with sulphate of copper -	1·1707	9 ·25	5·42
Water saturated with chloride of sodium at 9°·50 - - -	„	13 ·40	31·52
Water saturated with nitrate of copper -	1·6008	13 ·00	89·95
Water saturated with sulphate of zinc -	1·4410	14 ·40	5·77
250 grms. of water, and 30 of iodide of potassium - - -	„	12 ·50	11·20
220 cent. cub. of water, and 20 of sulphuric acid with 1 atom of water - - -	„	19 ·00	88·68
Nitric acid of commerce at 36° - - -	„	13 ·10	97·77
30 grms. of protochloride of antimony, 120 cent. cub. water, and 100 cent. cub. hydrochloric acid - -	„	15 ·00	112·01

We should notice, that the saturated solution of nitrate of copper, when diluted with water so as to occupy a double volume, has a conducting power which is almost double, 17·073 instead of 8·995; and sulphate of zinc, under the same conditions, has a conducting power of 7·13 instead of 5·77. This is also the maximum of conductibility for these two saline solutions.

The influence of temperature is very sensible upon the conducting power of liquids for electricity; but this influence here exerts an action contrary to that which it exercises over

metals; namely, elevation of temperature increases instead of diminishes the conducting power of liquids. This fact had been pointed out by M. Marianini in 1826, who had noticed that the intensity of the current of a pair was increased by heating the liquid of this pair; but here the effect was complex, because it might be equally well traced to an increase produced by heat in the electromotive action of the metals of the pair, as to an increase in the electric conductibility of the liquid. More recently MM. E. Becquerel and Hankel have proved in a direct manner that the elevation of temperature does actually increase the conducting power of liquids. M. E. Becquerel for this purpose employed the same means that had served him for measuring the actual conductibility of liquids; and the following are the results, that he obtained with three liquids. The conducting power of each of them being considered as unity, the conductibility for an increase of temperature of one degree increased; —

For saturated solution of sulphate of copper - -	0·0286
For diluted solution of sulphate of zinc - -	0·0223
For nitric acid of commerce - - - -	0·0263

Which shows for each of these liquids an increase of more than $\frac{2}{100}$ of its conductibility for one degree of elevation of temperature.

M. Hankel's experiments were made according to a method very similar to that of M. E. Becquerel, by means of a differential galvanometer; between the two wires of which a current, produced by two or three pairs of Daniell's, is so divided as to traverse them in opposite directions. In the circuit of one of the wires was included the liquid, that is the subject of the experiment, placed in a U tube; and in the circuit of the other helices of iron wire, the resistance of which was exactly known, and the lengths of which were varied until they presented a resistance equal to that of the liquid column, which occurred when the needle remained at 0° at the moment when the entire circuit was closed. M. Hankel took the precaution never to allow the current to pass for more than a very short instant; so that he might prevent the

polarisation of the electrodes, and also the elevation of temperature, that arises from the passage of the current, from introducing disturbances into the results. He found by this method, that the conductibility of a concentrated solution of sulphate of copper increases on being heated from 0° to 83°, about in the relation of 1 to 3·6; that of a concentrated solution of nitrate of copper in the relation of 1 to 3; that of a concentrated solution of sulphate of zinc in the relation of 1 to 5·7. These results are notably more considerable than those obtained by M. E. Becquerel, as may be easily proved by multiplying the latter by 83, the number of degrees between which M. Hankel operated. This difference is probably due to M. Hankel's employing for electrodes plates of copper in solutions of copper, and of zinc in solutions of zinc, instead of platinum wires, as M. E. Becquerel had done. It followed from this, that the action of heat influenced the intensity of the transmitted current; not only by increasing the conductibility of the liquid, but by facilitating the passage of the electricity by means of the solution of the plates in this liquid; the effect was therefore complex, which proves that M. Becquerel's results represent better the special influence of temperature, over the conductibility proper of the liquid.

In these phenomena the influence of the electrodes, that is, of the metals by which the current is transmitted into the liquid, is indeed very great; so that, as I have remarked, we have merely to heat powerfully a platinum electrode, without sensibly raising the temperature of the liquid, in order to facilitate in a very notable manner the transmission of a current, and to raise, for instance, its intensity, as shown by a galvanometer, from 12° to 30°; but what is very curious is, that this result is obtained only when the heated electrode is the negative one; the heating of the positive electrode has no influence. This effect is due, as we shall see, to a chemical action facilitated by heat, that destroys the polarisation of the electrode; which polarisation contributes to diminish the intensity of the transmitted current.

M. Vorselmann de Heer, after having confirmed the results

that I had obtained, showed that we have merely to move violently the negative electrode in order to make a current rise from 34° to 40°; whilst the moving of the positive electrode scarcely produces any change in the force of the current. These effects, as M. Beetz has very well demonstrated, are due to either the action of heat, or the mere mechanical motion destroying in certain cases the polarisation of the electrodes, which contributes to diminish the intensity of the transmitted current. We shall return to this important point when we have studied the cause of the polarisation of the electrodes, which is the deposition upon their surface of elements arising from the chemical decomposition of the liquids.

Heat exercises another kind of influence over the conductibility of bodies; it is to convert into conductors, by making them pass into a liquid state, a considerable number of compound bodies which in their solid state were incapable of transmitting a current, or transmitted it in a very imperfect manner. This important discovery is due to Faraday.

The following is the list of the principal substances, that he has found susceptible of becoming conductors, when they are liquefied by heat from being insulators, when in a solid state.

1st. Ice, or congealed water.

2nd. Among oxides, that of potassium, the protoxide of lead and that of antimony, the oxide of bismuth, and glass of antimony.

3rd. The chlorides of potassium, of sodium, of barium, of strontium, of magnesium, of manganese, of zinc, of lead, of antimony, of silver, and the protochlorides of tin and copper.

4th. The iodides of potassium, of zinc, of lead, the protiodide of tin, and the periodide of mercury.

5th. The sulphurets of potassium and of antimony.

6th. The chlorate of potash, many nitrates, sulphates, &c., &c.

Among the bodies in which igneous fusion does not develope conducting power we may mention, besides sulphur, phosphorus, camphor, &c., the periodide of tin, the sulphurets of arsenic (orpiment and realgar), &c. Melted glass, especially

flint-glass, becomes a conductor when raised to a high temperature.

What is very remarkable is, that the mere softening of a body by heat is not sufficient, in general, except in certain exceptional cases, to render it a conductor; it is necessary for it to become completely liquid; which would prove that the effect is less due to the elevation of temperature than to the liquefaction of the body. Mr. Faraday observed this, particularly with borate of lead.

We need scarcely state that Faraday, in all his experiments, determined conductibility by the faculty, either possessed or acquired by a body, of transmitting a current capable of acting upon the magnetised needle, or of producing decomposition. We shall see in the following paragraph, that in respect to imperfect conductors, in which the propagation of electricity occurs slowly, the mode of observation is different.

It is probable that this effect of heat is due to the circumstance, that the transmission of the current cannot take place in compound bodies unless they are at the same time decomposed; and that decomposition itself can be effected only while they are liquid. However, Faraday thought he had found some bodies—such, for example, as periodide of mercury,—which, although insulating when solid, become conductors when they are liquid, without undergoing, in appearance at least, any sensible decomposition. He also found that sulphuret of silver and fluoride of lead, which at the ordinary temperature are insulators, become conductors by the mere elevation of temperature, without the necessity of passing into the liquid state. When once melted, they conduct electricity as well as metals do, and do not appear to undergo decomposition. When they become solid again, and have been brought back to their original temperature, they again become insulators; which seems to prove that their chemical nature has not been altered by heat. Glass also exhibits the same conditions. However, it is still a controverted question, which will be discussed in the Chapter on electro-chemical decompositions, namely, whether a compound

body is able to conduct electricity, if not entirely, at least in part, after the manner of simple bodies, without undergoing decomposition.

Then, also, we shall study the influence of water, which, although a very bad conductor in itself, is able in certain cases to convert into conductors, by admixture with them, not only the solid bodies that it dissolves, but liquids which are very insulating, such as bromine, melted iodine, and liquefied chlorine. There is evidently in this action of water, as well as in that of igneous liquefaction, a facility supplied for electro-chemical decomposition, and, consequently, more a chemical than a physical effect. Moreover, without now insisting upon this subject, I may find a proof of it in the observation that I had made in 1837, and which M. E. Becquerel has confirmed, as we have already seen above, that mercury, although liquid, loses by heating a notable part of its conducting power; contrary to what happens with all liquids, which, instead of being simple bodies, are compound substances.

Before terminating, we will again mention the important results obtained by M. Matteucci, who has submitted to experiment a great number of combinations, which he was enabled to obtain in a state of purity, and which satisfied the double condition of being anhydrous and fusible. A voltameter was placed in the principal circuit, which was subdivided into two; one containing a second voltameter similar to the first, the other the compound substance in a state of igneous fusion. If the indication of the second voltameter was the same as that of the first, it was a proof that the melted substance was not conducteous; if, on the contrary, this indication was less or null, it might be concluded that a portion or the whole of the current passed through the body that was the subject of the experiment. It is by this process that M. Matteucci had obtained the results that we have related above, on the conducting powers of acids at various degrees of concentration. In a state of fusion, the protoxide and the iodide of lead, the chloride of silver, the protochloride of copper, the sulphurets of antimony, and of potassium, the

nitrates of potash and of silver, conducted the whole of the current, and do not allow of any portion passing through the voltameter; then, in their order of conductibility, come chloride of lead, iodide of potassium, the chlorides of sodium, of calcium, and of zinc, the bi-iodide and the protochloride of mercury, the chloride of antimony, and the protochloride of tin. The bichlorides of tin and of antimony caused the current to pass entirely into the secondary voltameter. Aqueous solutions of these combinations, in as concentrated a state as possible, were then compared with the same bodies in the state of igneous fusion; and it was found that all the current passed into the melted combination, even when the solution was heated. However, there is a very evident relation between the conductibility of a solution and that possessed by the body, that had been dissolved, when in the state of fusion; then, in order that two aqueous solutions shall have the same conductibility, it is necessary that the one whose compound when in a state of fusion is the worse conductor, should be more concentrated. This consequence seems clearly to prove, that in the aqueous solutions of certain compound bodies, whose conductibility when in a state of fusion is great, the current is conducted by the dissolved body, and that the only function of the water, like that of heat, is to impart to it the liquid state essential to electro-chemical decomposition.

Another very important observation of M. Matteucci's is, that certain bodies, which do not conduct when in a state of fusion, such as the bichlorides that we have mentioned above, acquire this property when they are dissolved in water; probably because the presence of water facilitates their decomposition. In like manner the chlorides of antimony, and the protochloride of tin, which are very bad conductors when in a state of igneous fusion, are much better when they form in water very concentrated solutions. It is evident that in all these phenomena there are secondary chemical actions, which the passage of the current brings about and facilitates, and which cause these effects to be very complex.

We may, therefore, sum up this paragraph by saying; 1st,

That metals and carbon have a conductibility proper, which varies with their nature and with their molecular state; 2nd, That elevation of temperature diminishes in all of them their conducting power, in a proportion which is variable for each with their nature and their molecular condition; 3rd, That solid compound bodies, which are insulators at the ordinary temperature, become conductors on being heated, but that the greater number acquire this property only when they are heated sufficiently to pass into the liquid state; 4th, That for aqueous solutions, the conducting power varies with their degree of concentration, the most concentrated being generally, unless in certain exceptional cases, the best conductors, and that this power generally increases with the elevation of temperature; 5th, That the differences which exist between simple and compound bodies, as far as the influence of heat is concerned, seems to indicate that their conductibility, or what comes to the same thing, their mode of propagating electricity, is not completely identical, which is due probably to the circumstance that in compound bodies the transmission of the electric current is either always accompanied by a molecular change, or more frequently, if not always, by a chemical decomposition; 6th, It follows from this last circumstance, that the subject of the electric conductibility of compound bodies cannot be completely discussed, except by studying electro-chemical decompositions, which form the subject of a distinct Chapter in this Fourth Part.

Propagation of Electricity in Imperfect Solid and Liquid Conductors.

When in the First Part of this Treatise we gave the list of conducting and insulating bodies*, we were careful to remark that conductibility is not an absolute property; namely, that we cannot class bodies into two categories, one of which shall consist of perfect conductors, and the other of perfect insulators. We have been engaged in the preceding para-

* Vol. I. p. 8.

graph with those which are sufficiently good conductors to be able to transmit voltaic electricity in a continuous and rapid manner; a property that is made manifest by the dynamic effects of the current. We will now go on in this paragraph to study the propagation of electricity in bodies of which several are regarded as insulators, or which at least conduct electricity too imperfectly to be able, unless under certain exceptional circumstances, to transmit a current properly so called.

Priestley had long ago remarked that ice, glass when heated or when pounded, the flame of a candle, and a great number of mineral substances, are able to transmit the discharge of a Leyden jar, or even that of the charged conductor of an electrical machine. Coulomb, in his admirable works on the slow loss of electricity, was satisfied that cylinders made of substances apparently the best insulators, such as glass, sealing-wax, and gum-lac itself, transmit difficultly it is true, but in a sensible manner, the electricity accumulated upon the conductor of an electrical machine with which they are placed in contact by one of their extremities. This may be proved either by the loss of electricity suffered by the conductor, or by the electric action that these insulating substances become capable of exerting, which proves that they are impregnated with electricity. However, Coulomb found, that when the intensity of the electricity is not very strong, a thread of gum-lac of $\frac{1}{25}$ in. in diameter about 2 in. in length is sufficient to insulate completely a cork ball $\frac{1}{2}$ in. in diameter. But, as we see, this insulating property is not absolute; for Coulomb himself observed, that the degree of electric reaction at which very fine cylindrical supports commence to insulate is, from the same state of the air, proportional to the square root of their length. In order to ascertain the permeability of all substances that transmit electricity imperfectly, it is necessary to determine the intensity of the electric reaction at which insulation commences for threads of the same length and the same diameter, but of different natures. By this means Coulomb found that the value of this reaction is ten times greater for a thread of gum-lac than for one of silk.

Riess has submitted to experiment a certain number of substances, in order to determine whether they are conductors or not. By conductor he designated a body that instantaneously takes away the electricity from a charged electroscope with which it is put into contact; by imperfect conductor, that which does not carry it away until after an interval of several seconds; and by non-conductors, that which at the end of some minutes has not in a sensible manner modified the divergence of the gold-leaves of the instrument. The last distinction is rather arbitrary. He has thus found that a cylinder of selenium three or four-tenths of an inch in diameter, and $\frac{1}{2}$ in. or 1 in. in length, instantly carried off the electricity of an electroscope with which it was placed in contact; but that when drawn into a fine wire by the flame of a lamp, it was as good an insulator as a thread of gum-lac. Selenium belongs therefore to non-conducting bodies, and friction easily renders it electrical, provided its surface be very smooth. Iodine is an imperfect conductor; cylinders $\frac{1}{2}$ an inch in diameter, and of various lengths, discharge an electroscope in a second, but cannot transmit a voltaic current. Aluminium and beryllium in powder, rammed into glass tubes terminated by metal points, very quickly discharge electricity from the electroscope; but Riess satisfactorily proved that these two substances owe this property merely to the presence of condensed water; for by drying them for half an hour in porcelain crucibles at the temperature of 212°, they become non-conductors. Beryllium is even so good an insulator, that a layer of less than $\frac{1}{25}$ in. in thickness does not alter the divergence of the electroscope; with aluminium, in order to obtain the same result, it is necessary that the layer be at least $\frac{1}{5}$ in. thick.*

This last observation shows how difficult it is, when experimenting with bodies which are only imperfect conductors, to avoid the different causes, that may lead to erroneous

* M. Deville has found that aluminium, to which he has succeeded in giving the consistency of the ordinary metals, is an excellent conductor of electricity, and almost as good as silver. It is probable that its imperfect conductibility was due to the particular condition in which it occurred in M. Riess's experiments.

results. M. Karsten points out one that is also calculated to explain the contradictory conclusions to which many philosophers have arrived who have been engaged upon this subject; it is the different manner of preparing the bodies that are the subject of experiment. Thus, being desirous of determining the conducting power of the sulphurets of the different metals, he remarked that sulphuret of antimony in the state of powder is a perfect conductor; whilst, when it has been melted and cooled in a mould, it becomes an insulator. It is true that it is then covered with a vitrified film, which envelopes a crystalline core; whilst, when the cooling occurs very slowly, the whole mass acquires the crystalline texture, and comports itself as a conductor. But, on the other hand, sulphuret of antimony produced by the moist process is a perfect insulator. It is the same with the sulphurets of cadmium and of zinc; but prepared by the dry process they are conductors. The sulphurets of tin, copper, lead, bismuth, and iron are always conductors, by whatever process they may have been prepared; the black sulphuret of mercury is a good conductor, whilst cinnabar conducts very feebly; finally, the sulphurets of gold and of silver prepared by the moist process are conductors.

There also exist certain liquids which, although regarded as insulators, are in fact nothing less than imperfect conductors; such, for example, are the different kinds of oils, which in this respect present among themselves very remarkable differences. M. Rousseau, who was the first to observe these differences, used for this purpose an apparatus of his own invention; which consists of a horizontal needle movable on a pivot, by means of which communication may be made with one of the poles of a dry pile, while one of its ends is very near to a fixed ball communicating also with the same pole.* If communication is made by a body that is more or less a conductor, the needle is driven from its normal

* For his movable needle M. Rousseau employs a magnetised needle, so that it might always return to the same position when no action was occurring; but an unmagnetised needle, one of copper, for instance, accomplishes the object equally well, and gives a more sensible result.

position; after having accomplished a few oscillations, it assumes a position of equilibrium that is dependent on the force of the pile, which may be considered as being constant for the same pile for a long time. Now, in order to employ this apparatus for investigating different degrees of conductibility, we have merely to place in the course that must be traversed by the electric fluid the different bodies which we propose subjecting to experiment, with the precaution of arranging that the thickness to be traversed by the electricity shall be always equal; if the passage of the quantity of electricity necessary for producing the greatest deviation is not instantaneous, the time that will be required by the needle in order to arrive at its stable position may be taken as the measure of the degree of conductibility of the compound substance. In order to submit liquids to this kind of test, M. Rousseau places them in small metal vessels, which communicate by their foot with the needle and the ball; then he plunges into the liquid one end of a wire, partly covered with gum-lac, in order that the same surface of metal may always be in contact with the liquid; he then measures the duration of the movement of the needle, setting out from the moment when communication is established by the other end of the wire with one of the poles of the pile, whilst the other pole is in communication with the ground.

In operating with different oils, M. Rousseau observed this very curious fact, that olive oil possesses very inferior conductibility to that of all other vegetable or animal oils. Thus, in order to produce a certain deviation, everything being similar in other respects, it required 40′ for olive oil, and only 27″ for oil of poppies. By merely adding to olive oil a hundredth part only of another species of oil, the term required for producing the same effect was reduced from 40′ to 10′. Solid fats do not conduct so well as animal oils; which is due, as may be proved in a direct manner, to the greater proportion of stearine in the former than in the latter. M. Rousseau was unable to detect any difference in the conducting property of spirituous, aqueous, acid, alkaline, or neutral liquids; for with these various substances the time

required by the needle in order to attain its maximum of deviation, is too short to enable us to appreciate any inequalities of duration. But these inequalities are very sensible, when we subject to this test resin, gum-lac, or sulphur; substances which are found to be much better insulators than silk, crystal, and common glass. It would be easy to modify M. Rousseau's apparatus, so as to render it susceptible of indicating differences between bodies which are less distant from each other in respect to conductibility; but in all cases it would only give the order of conducting power, more or less imperfect of bodies; and never their relations of conductibility.

Before pursuing the explanation of the experiments that have been made upon the various degrees of conductibility of imperfect conductors, let us devote a short time to the manner, in which the propagation of electricity takes place. We have already given* Mr. Faraday's experiments and theories on this subject, in connection with his experiments on dialectric bodies, as well as the researches of Harris and Matteucci. Faraday's fundamental idea is that the propagation of electricity in bodies, that are more or less insulators, is brought about by the polarisation of the successive molecules; and that each body possesses in this respect a specific power that is peculiarly its own. Matteucci had already confirmed this theory by his remarkable experiment with superposed plates of mica, which became polarised, that is to say, they acquired on each of their faces a different electricity, when they are interposed between two armatures highly charged with contrary electricities; but he has further demonstrated, by direct experiments, that molecular electrisation is developed in different degrees in different insulating bodies. Thus he made a small pendulum oscillate, to which he had given electric charges of greater or less intensity, before three spheres of very great diameter, in comparison with that of the electrised ball. The three spheres, placed successively at the same distance from the electrised pendulum (first, at

* Vol. I. p. 139. and the following pages.

a distance of 4 in., then of about 5 in.), were a sphere of lead, one of sulphur, and one of resin. The mean duration of 20 oscillations, at a distance of 4 in., with a certain electric intensity, was, for the sphere of lead, $24\frac{1}{2}''$, for that of sulphur, $30\frac{1}{2}''$, for that of resin, $32\frac{1}{2}''$; with another intensity and at a distance of about 5 in., these numbers were different, but their relations remained almost the same; which gives for the mean of the numbers, that represent the relation of the forces, —

Sphere of lead	-	1·
„ Sulphur	-	0·6072
„ Resin	-	0·4800

Thus at a distance spheres of a different nature experience a different influence from the electricity of the pendulum; but it is independent, in regard to its relative intensity, of the energy of the electric charge.

When in contact these differences are more sensible. In order to estimate them, M. Matteucci employed plates and cylinders made of different insulating substances, which he touches successively with an electrised metal ball held by an insulating handle, or with a cylinder of gum-lac electrised by friction; he then brings the plate or cylinder, that has been touched, in front of a small electric pendulum. If the body that has electrised is an insulator, the point of the plate or cylinder that is touched is found charged with a contrary electricity to that of the electrised body, and around this point with similar electricity. If the body that has electrised is a conductor, the insulating plate or cylinder is soon found to be charged with the same electricity as this body, provided the insulating substance is not of a large mass, and that the contact has not been maintained longer than a brief moment; in which case the touched points have a contrary electricity to that of the electrised conductor.

Furthermore, the propagation of electricity in an insulating body may be easily proved by direct experiment. For this purpose we have merely to electrise a cylinder of stearic acid by means of the prime conductor of the machine; if it

is rubbed with woollen cloth, signs of negative electricity are obtained; but, in order to obtain the re-appearance of the signs of positive electricity that had been communicated to it by the electrical machine, and which has become propagated in its interior, we have merely to melt the surface, or to wash it in sulphuric ether.

The laws of this propagation have been the subject of long and delicate researches on the part of M. Matteucci. By operating with the balance of Coulomb — and after the movable ball had receded about 30° from the fixed ball by introducing an insulating plate, which he placed in contact with this ball—he deduced, by the determination of the distance between the two balls, the facility with which the insulating plate had taken away electricity from the fixed ball, and, consequently, its degree of aptitude in propagating electricity. He took the precaution of allowing contact to remain in each experiment for five minutes; and he estimated by the diminution of the angle of torsion, after the insulating plate had been removed, the quantity of electricity that it had taken away from the fixed ball. The experiments were made by varying the initial charge of the ball and the extent and thickness of the insulating plate, and by operating for the most part with plates of sulphur; but sometimes also with plates of gum-lac, glass, and mica. In each experiment a note was made of the initial electric force, of the electric force during the contact of the insulating plate, and, finally, of the *residual* force; namely, that which remained after a contact of five minutes. During these five minutes, the loss of electricity by the air was absolutely insensible.

The results of the numerous experiments, made in this manner by M. Matteucci, do not lead to very simple laws; but the results are not the less curious. Thus, the quantity of electricity taken from the ball by the insulating substance is proportionately greater as the electric charge is stronger; it is in like manner more considerable in proportion as the insulating plate is thinner and less extended; which is due to the effect being concentrated on a smaller number of points, and being consequently proportionately greater. It follows,

that the passage of electricity from a metal ball to an insulating body occurs the more easily in proportion as the latter is thinner, and presents to the ball the smallest number of points that do not touch it; so that an electrised metal ball would lose the smallest possible quantity of electricity when resting on a very thick and very extended insulating disc; and that, on the contrary, the greatest loss of electricity would occur on reducing the insulating body to a very slender and very short stem.*

If the insulating discs, whatever their nature be, are covered with a thin sheet of tin-foil on one of their faces, whilst the other is in contact with the movable electrised ball, we find that the electric force of the ball diminishes much more, both during and after this contact, than when the insulating disc is not coated: these results seem to demonstrate the penetration of contrary electric charges, that takes place in the two faces of the insulating disc,—the one by contact, the other by induction—a penetration, which may easily be proved directly. For this purpose, we have merely to take a cubical piece of spermaceti, and to place it between two coatings, so as to constitute a magic pane, which is charged feebly but tediously. Then, by means of plates of glass, the piece of spermaceti is to be divided into several fragments, which are found to be charged to a certain depth with positive electricity on the side of the positive coating, and with negative electricity on the side of the negative coating. If in place of spermaceti, we employ plates of mica superposed on each other, instead of having contrary electric states on the opposite faces of each of them, providing a powerful electric force is employed and allowed to act for a long time, we end by finding the same electricity upon both faces of the same plate, going from the outer plates toward the middle; namely, positive electricity upon the plates that are on one side, and negative upon those which are on the other.

M. Matteucci concludes from these experiments, and from

* This result agrees with Coulomb's observation, that, in order to produce a perfect insulator, a thin stem should be longer in proportion as the substance of which it is made is a less efficient insulator.

others that we have already * mentioned that the difference observed by Faraday and Harris, between different substances with regard to their faculty for modifying the electric charge of the magic pane, between the two coatings of which they are placed, is not due to their specific inductive power, but simply to differences in the propagation of electricity, either at their surface or at a very small depth in their interior: a proof that the electric molecular states may be destroyed in insulating bodies, and electricity may be propagated in them as in conductors, and that insulating power consists merely of the greater or less resistance to the successive establishment and destruction of the molecular electric states. We may also remark that this molecular electrisation is developed and ceases in insulating bodies at the very moment when the presence of the electrised body commences or ceases.

It is a very remarkable fact that negative electricity is propagated more readily than positive, both on the surface and in the interior of insulating bodies. The experiment is made by charging balls, sometimes with negative, sometimes with positive electricity, and by comparing the results obtained, on placing in each case the movable ball in contact with the uncoated surface of the insulating plate, the coated surface being in communication with the ground. The differences are very decided; the diminution of the electric force during contact, and of the force that remains after contact, is greater for negative than for positive electricity, in the relation of double to single. The difference is not so great, although it is still sensible, when the insulating plates are not coated; but it is more considerable in proportion as the electric charge is stronger. It is evident that to this different property of the two electricities is to be traced the cause of the Lichtenberg † figures, in which positive electricity is propagated on an insulating surface in ramifications, consequently, in compacted filaments, distributed unequally over this surface, whilst negative electricity is propagated uniformly in radii equally distributed around the electrised point.

* Vol. I. p. 152. † Vol. I. p. 111.

We may further add, that differences of temperature, even the slightest, produce a considerable variation in the insulating power of bodies; but these variations do not follow the same progressions in different substances. Thus, with very strong electric charges, sulphur up to 68° is not so good an insulator as gum-lac; the reverse is the case beyond 68°. In order to determine accurately the difference in the two cases, two cubes of 2·36 in. on each side are taken, the one of sulphur, the other of gum-lac; each of these cubes is cut through the middle, and a spherical cavity is made in its centre of the size of the movable ball, which lodges in it as in a mould. These cubes being well-dried, the ball is placed in them for a few seconds: it is found that the loss of electricity at 56°·8 being $\frac{1}{337}$ in air, it is $\frac{1}{37}$ in gum-lac, and $\frac{1}{31}$ in sulphur; and at 95°, $\frac{1}{21}$ in gum-lac, and $\frac{1}{40}$ in sulphur.

We must not confound this influence of heat with that which consists in removing from the surface of certain bodies, such as glass and mica, a thin layer of moisture, which renders them slightly conductors. In this case the elevation of temperature increases their insulating power. But a more powerful heating diminishes it; glass, resin, and wax, become conductors at a temperature sufficient to soften them, and still more so, when they are reduced to the state of liquid. Glass in a state of fusion is even able to conduct a very feeble current, so as to act upon the galvanometer. It is true that under these conditions, it probably experiences an alteration in its chemical constitution, which may explain the modifications brought about in its insulating power; the same thing also occurs when its surface has been radiated by electric discharges; indeed, it may be seen that the rays are much better conductors than the rest of the surface, which has not been altered by the passage of discharges. However, a simple modification in the arrangement of the particles is amply sufficient, without any chemical alteration, to account for the changes that may occur in the conductibility of bodies that are imperfect conductors; and we find a remarkable proof of this in the conducting properties of crystals,

which have been studied with great care, successively by M. Wiedemann, and by M. de Sénarmont.

The former of these philosophers, in pursuing these investigations, made use of powder of lycopodium or minium, with which he powdered over the surface of the body submitted to experiment; he then touches a point of this surface with the point of an insulated needle, by means of which he communicated positive electricity from a Leyden jar. The light powder is dispersed all around the point, by the effect of the repulsion exercised upon it by the points of the surface, that have received the electricity. When the body powdered upon is a plate of glass, a circular figure is obtained around the point, traversed by rays similar to the Lichtenberg figures. When, instead of glass, a pallet of gypsum is employed, the powder is no longer dispersed in a uniform manner in all directions. Two principal directions are noticed which are diametrically opposite, and along which the dispersion occurs with more force; this gives rise to an elliptical surface, whose axes are to each other as 2 or 3 is to 1. The great axis of this ellipses forms a right angle with the principal crystallographic axis, which proves that electricity is more easily distributed in a direction perpendicular to the principal axis, than in any other direction. The same phenomenon is presented with many other crystals, such as celestine, quartz, acetates of lime and copper, which are all positive. On the other hand, with negative crystalline substances, such as arragonite, tourmaline, and Iceland spar, the axis of the ellipse, formed by the electric dispersion of the powder, is parallel to the crystallographic axis. These opposite results seem to indicate, that the direction of best electric conductibility is also that in which light is propagated relatively with most rapidity.

M. de Sénarmont, who had already discovered the unequal conductibility of crystals for heat in different directions, had arrived at the same time as M. Wiedemann * at analogous

* The researches of M. Wiedemann appeared a short time before those of M. de Sénarmont; but the processes of the two philosophers, although their results generally agree, are very different.

results, as far as the conducting power for electricity is concerned. M. de Sénarmont covers the surface of bad conducting bodies with a sheet of tin-foil, forming as it were a metal envelope around the body; he takes care to perforate this envelope with a perfectly circular hole, which exposes a part of the natural surface. An insulated metal point, placed in the centre of the opening, perpendicular to the surface itself of the bad conducting body, is the way by which the electricity is introduced. The electricity cannot escape, except by traversing toward the circumference, and passing over a non-conducting space; it has, therefore, to overcome resistances, the evidence of which is manifested by luminous phenomena. As every thing is symmetrical, the electricity that enters at the centre of the circle, is attracted equally on all sides by the conducting circumference, and cannot be led in greater proportion in one direction than in the other, except by differences in superficial conductibility. There is an advantage in operating in rarefied air, because the phenomenon is in this way well regulated; it is true that the continuous escape of electricity does not, in this case, leave any permanent traces; but it is manifested in darkness by a light, which renders all the peculiarities of the phenomenon visible during its continuance.

Experiments conducted in this manner show that upon homogeneous matters, or upon crystals of the regular system, electricity spreads circularly around the central point, and covers the surface of the circle with a uniform light; it is the same with crystals of the prismatic system, with a square and rhombohedral base, but only when the face is normal to the axis of symmetry. In all other cases, namely, on the faces parallel and inclined to the axis of symmetry of crystals of this system, on any face whatever, as well as with crystals of other systems, there exists a direction of principal conductibility. In such cases, we see plainly the light escaping freely from the centre in two opposite directions, and thus forming a luminous diameter, which assumes a fixed direction, or spreads a little into a fan, and balances itself by a few slight oscillations on the right and left of its true

direction. The direction is more stable, when a certain tension is allowed to the air; sometimes, even in this case, brilliant and instantaneous sparks intermingle with the permanent violet light; and, if the surface has been powdered with flowers of sulphur, the sparks leave upon this powder the trace of the rectilinear course which they have traversed.

The results obtained by M. de Sénarmont show that, when the face of the crystal contains in its plane one or two axes of symmetry, the direction of maximum conductibility is perpendicular or parallel to these axes; but that, in other cases, namely when the face contains no axes of symmetry in its plane, this direction cannot be anticipated *à priori*; it must be determined by experiment, and does not necessarily coincide either with the directions of the axes of optical elasticity, or with the directions of the axes of thermic conductibility. However, the analogies that are presented by the optical, calorific, magnetic and electric properties of crystals, which we have previously entered into*, and the influence exercised over these properties by the equal or unequal axes of symmetry, are of a nature to demonstrate that they are connected with a common cause, namely, molecular arrangement, and to show the importance of this cause in the phenomena that are now engaging our attention. M. Knoblauch has on his part actually demonstrated the influence of crystalline form over induced electricity, by observing that crystals, suspended between the contrary poles of two dry piles, assume a determinate direction, which is due to the mode in which their particles are grouped.

We may further add that M. de Sénarmont, as well as M. Wiedemann, has remarked a very decided difference between positive and negative electricity, with regard to their mode of action in experiments relating to the superficial conductibilty of crystals. The results are, however, very confused and variable, when negative electricity is made to enter by the point; they are well determined with positive

* Vol. I. p. 515.

electricity alone. We shall return to these differences presented by the two electricities; but we must first point out one, which was only apparent, and has admitted of explanation by the ordinary and known effects of the electric current.

Ermann thought he had found in a particular class of imperfect conductors, which he had called *unipolar*, the property of more easily transmitting one of the electricities than the other. Into a piece of very dry soap, he introduced two wires communicating respectively with one of the poles of a voltaic pile; the two poles preserved their tension; but if the soap was touched with a conducting body, the negative pole was discharged, whilst the positive pole acquired the maximum of tension that it possesses when, with the pile in an insulated state, the negative pole is put into communication with the ground. Ermann had discovered the same property in dried white of egg, and in the flame of phosphorus; he had also noticed it in the flames of hydrogen, of alcohol and of hydro-carbon bodies in general; but with this difference, that it is the positive pole that is discharged by these flames, whilst the negative pole acquires its highest tension. The former had consequently been designated negative unipolar, the latter positive unipolar, bodies. This classification, in addition to its having been too absolute in its character, had the further defect of being based upon an erroneous interpretation of the experiments. Indeed, Ohm has demonstrated that the cause of the phenomenon observed by Ermann does not reside in any property of the substance interposed between the poles of the pile, but is due to the effect produced in it, as soon as the circuit is closed, by the current that traverses it. This effect consists of the decomposition of the soap, the stearic or oleic acid of which is carried to the positive pole, whilst the soda goes to the negative; these acids being of an insulating nature, as soon as they have covered the wire upon which they are deposited, the electricity of the pole with which this wire is in communication, namely, the positive, can no longer pass in the soap, whilst the negative continues to be transmitted in it and escapes thence into the

ground. Thus the negative pole of the pile is discharged, whilst the positive maintains its tension. This very natural interpretation of Ermann's experiment is found to be confirmed by a great number of facts. Indeed, we have merely to put the wire that came from the positive pole into communication with the negative pole, and which consequently is covered with the coat of acid, and we insulate the negative electricity as had been the case with the positive. In order to succeed in these experiments, it is necessary to have a powerful pile; for, unless this is done, the products of decomposition occur in so small a quantity that they cannot interpose any obstacle to the circulation of the current.

With regard to the unipolarity of hydrogenous flames, it is probably due to the voltaic decomposition of the vapour of water formed during combustion, — a decomposition that determines upon the surface of the negative wire the deposit of an insulating film of hydrogen; whence it follows that the positive electricity alone is able to pass away into the ground by means of the wire placed in the flame. We shall elsewhere return to the phenomena connected with the conducting powers of flames in the following paragraph, which is devoted to the propagation of electricity in elastic fluids.

Concentrated sulphuric acid, when placed under the same conditions as soap and flames, is a negative unipolar conductor which arises from the formation on the positive wire of insoluble and non-conducting sulphate; but the effect varies with the nature of the wires immersed in the acid; inasmuch as some form more soluble and better conducting sulphates, than are formed by the others. Finally, all this class of phenomena is nothing more than the result of the secondary actions, which always accompany the transmission of electricity through conductors, capable of being decomposed; and under this view, it loses much of its theoretic importance, and enters into the category of the numerous facts due to the same cause, and which we shall study in the Chapter on electro-chemical decompositions.*

* In what we have been saying upon unipolar conductors, we have not mentioned some experiments of Ermann's, relative to the reciprocal insulating and

Hitherto, while engaged with imperfect solid and liquid conductors, we have spoken only of the slow and gradual propagation of electricity that can be brought about in them; but these conductors are able to transmit electricity, according to a very different mode, namely, suddenly and instantaneously. This mode of transmission in such bodies is attended by a rupture in their molecular equilibrium, which is manifested under different forms, but which always occurs; it is also frequently attended by luminous, calorific, and chemical effects; but the production of these effects is not a necessary condition of the transmission of electricity: we shall study these effects in the sequel, in the Chapters that are appropriated to them, whilst the molecular phenomena being connected with the very mode of propagation in question, we cannot separate the study of them from that of this mode of propagation.

When a thin plate of glass or mica is placed between the two extremities of the rods of a discharger, it is, as we have already seen, pierced with a hole, by the discharge of an electric battery; it is the same with a piece of dry wood, which is split and broken into a thousand fragments, that are dispersed about in all directions. The edges of the hole, when glass or mica is employed, become opaque; we perceive that the molecular condition of the substance has been altered. If the two extremities of the rods of the discharger are placed at some little distance apart, but on the same side, on the surface of a plate of glass, the discharge occurs by means of a spark, which passes over this surface, leaving upon it traces, that cannot be obliterated, of the route it has followed. On hard glass, and rock crystal, these traces are pale, of a dull grey, and perfectly resist under the nail, as if the polish of the surface had been altered by rubbing it with coarse sand. On soft glass, mica, and delicate crystals, the traces, left by

conducting action which the incandescent platinum of Davy's aphlogistic lamp exercises over the two electricities. These phenomena, in which it was at first thought that proofs were found in favour of Franklin's theory of a single electricity, are very complex; and depend essentially upon the production of electricity, which accompanies the slow combustion that takes place in the aphlogistic lamp. The study of these phenomena must therefore be postponed, until we are engaged with the different sources of electricity.

the discharge, present a different aspect: they seem to indicate that the matter has undergone a chemical change to a certain depth, a change that gives rise to the electric figures, observed by Riess, and by other philosophers; this chemical change almost always accompanies the mechanical effect; for the traces that are presented by the hardest glass upon its surface after the discharge, are slightly alkaline, as may easily be proved by rubbing them with paper reddened by litmus.

We have already quoted the experiment of the card, which, when it has been pierced by the discharge, presents bosses on both sides, and the hole of which is always opposite to the negative point, when the two points are not opposite to each other; which is due, as we shall see, to the unequal pressure experienced by the two electricities on the part of the air.

When the discharge traverses liquids, if they are imperfect conductors, or rather insulators, such as olive oil, sulphuric ether, and essence of turpentine, there is always a mechanical effect, accompanied by a spark. The vessel in which these liquids are contained, is frequently broken by the effect of even a moderate discharge: thus if it is of wood, it may be violently overturned by a spark, that is the length of $\frac{1}{25}$ of an inch; in order that it shall be broken, the spark must be a little more powerful. Singer succeeded in breaking into many fragments tubes of glass, whose sides were more than $\frac{2}{3}$ in. in thickness, by passing a discharge through a column of liquid, with which the tubes were filled; it is true that care was taken to close hermetically the extremities, by which the wires for transmitting the discharge had been introduced. The same effect is produced, when the tube is filled with a good conducting liquid, as mercury for instance, or sulphuric acid; but in this case the tube must be capillary and the length of the liquid column must not be too considerable. Morgan has remarked that with concentrated sulphuric acid, and a tube $\frac{1}{12}$ in. in diameter, the greatest length, at which the *breaking* and *luminous* explosion can occur at the same time, is about $19\frac{1}{2}$ in.

The passage of discharge through bad-conducting liquids, such as oils and essences, raises their temperature, and pro-

duces in them a deposit of carbon, arising from their decomposition; and in the end, their conducting power is slightly increased. This is probably an effect of the high temperature of the spark, rather than of the electricity itself; this we shall endeavour to investigate further on. Morgan, who was the first to observe this fact, also remarked that among liquids the oils are they which allow the discharge to pass the least easily, whilst alcohol and water, especially when heated, transmit it much better, so that in the latter instance it ceases to be luminous.

Moreover, the explosive effect of the discharge through conducting bodies occurs equally, whether they be solid or liquid, like mercury. Thus when a piece of very thin gold leaf is placed between two plates of glass, the upper of which is loaded with a weight, the gold is reduced to powder, and the plates are often broken in pieces.* In like manner, a very thin iron wire, one or two inches in length, when traversed by a discharge, that reduces it to powder, is capable of breaking into a thousand fragments a glass tube of about $\frac{1}{2}$ an inch across, in the interior of which it is placed; and these fragments are projected afar; care must be taken to introduce the discharge by means of two thick wires, each of which enters one end of the tube, and which are connected by the iron wire. If care is taken to surround this wire by a piece of paper, the paper is torn, but the glass is not at all damaged. The action is infinitely more violent, when the wire is surrounded by water or oil; this arises from liquids, which are incompressible or nearly so, transmitting in a much more complete and instantaneous manner than air, the pressure to which they are subjected. Pistol barrels may be split by filling them with water or oil, and taking the precaution of placing within the liquid, a thin band of lead, that is pulverised by the discharge.

In all cases, where the body that is traversed by the discharge is metallic, there is a great development of heat.

* We have already mentioned this experiment of the gold leaf, but under a slightly different form. See Vol. I. p. 121.

Is it to a sudden vaporisation, produced by this heat, that the mechanical effects we have been studying may be traced? This might be possible in the case of mercury; but this interpretation of the phenomenon becomes more difficult in the case of gold, and especially in that of iron. It would therefore seem that, independently of the heat which it developes, the discharge would produce, even in very good conducting bodies, when it meets with resistance, a mechanical rupture, and, as it were a kind of very energetic sudden expansion. However, this point deserves a very attentive examination: we reserve it until we shall be engaged upon the calorific effects of discharges, which are altogether connected with their mechanical effects, as Reiss has so well demonstrated.

In conclusion, all the phenomena presented by the propagation of electricity in imperfect conductors, whether it be slow or instantaneous, manifest the intimate connection existing between this propagation and the molecular condition of bodies. In the cases wherein the propagation is slow, every thing that modifies the molecular state has an influence upon it, as crystallisation, liquefaction, or the mere elevation of temperature. In the case, wherein the propagation is instantaneous, the molecular state is influenced by it. It is therefore very probable, that the sensible difference in this respect, existing between good and imperfect conductors, is due to the polarity of the atoms, which we have already established, being much more sensible in these latter. Indeed, the very imperfection of their conducting powers prevents the contrary electricities produced at their poles, namely, at the extremities of their axis, from uniting by their surface so easily as in the case of those bodies which are endowed with good conductibility; a polar state of the particles is the result of this, which compels them to change their position so as to arrange themselves in a manner harmonising with the two electricities, between which they are placed; whilst conducting particles only undergo the effect of induction, or of the artificial and not natural polarisation, that we have admitted in order to explain the manner

in which electricity is propagated in conducting bodies. We shall see many other proofs of this pre-existing polarity of the particles of non-conducting bodies, when we are engaged upon the development of electricity, to which these bodies give rise by the effect of the raising of their temperature.

Propagation of Electricity in Elastic Fluids.

Gases, when they are very dry, and especially atmospheric air, pass for being perfectly insulating bodies: however, they are capable of propagating electricity, more or less easily, it is true, according to their nature, and according to the conditions in which they happen to be placed.

Coulomb had long ago endeavoured to measure the loss of electricity, experienced by a well insulated electrised body, by means of the contact of the air. He had succeeded in eliminating the cause of loss that might arise from the insulating support, by employing as an insulator, a thread of gum-lac of $\frac{1}{27}$ in. in diameter and about two in. in length, and giving to the insulated body, which was a ball of elder-pith about $\frac{1}{2}$ in. in diameter, an electricity, that was not very powerful. This ball was placed in the torsion balance opposite to a movable ball, in like manner well insulated, since the needle by which it was sustained was also a fine cylinder of gum-lac; this movable ball possessed the same electricity. The loss of electricity, brought about by the contact of the air, became sensible by the gradual diminution of the repulsive force of the balls, which was measured by the diminution of the force of torsion necessary to maintain them at the same distance from each other, at 20° for instance. It was easy with a seconds' watch to determine exactly the relation existing between a certain diminution of the repulsive force, and the time necessary for producing this diminution. By comparing this diminution with the mean repulsive force between two consecutive experiments, Coulomb found a fraction, which expressed the proportion of the electric force of the two balls lost during a minute, at any moment. In the tables that Coulomb has given of these results, we find

that this fraction varies from $\frac{1}{14}$ to $\frac{1}{60}$: we also remark that for the same day and the same state of the air, the weakening of the electricity in a very short time is proportionate to its intensity; and that it varies according to a law difficult of determination, with the hygrometric state of the air. The nature of the substance of which the balls are made, does not appear to cause any influence on the loss of electricity, by the contact of the air. It is the same with their form, provided it is not angular,— a case as we know, in which electricity escapes from the body in an irregular manner. Coulomb found also that there was no difference between the two electricities, with regard to intensity and to the laws of their loss by contact with the air.

Faraday, in his researches on dialectric bodies, setting out, as we have seen, from the principle, that the communication of electricity is made by the polarisation of successive molecules, had submitted to experiment various gases and air in different states of density, by making use of the apparatus that we have described *, and which is intended to determine the specific inductive power of bodies. It consists, as may be remembered, of two veritable Leyden jars, perfectly similar, in which the insulating substances, interposed between the coatings, are those whose inductive powers are about to be compared. The learned English philosopher, by operating in this way, was unable to detect any sensible difference in this respect between the various gases and air, more or less rarefied, and more or less heated. Only, in these experiments, we must take care to avoid raising the electric tension to the point at which discharge would occur.

M. Matteucci has taken up the subject of the propagation of electricity in gaseous bodies; and has succeeded in determining its laws by a numerous series of experiments, made with great care. For measuring the electric forces, he made use of several Coulomb's balances, furnished with torsion threads of different lengths and diameters, according to the electric forces with which he was operating. Instead of employing, as Coulomb had done, balls of elder-pith, which

* See Vol. I. p. 135., *fig.* 67.

possess the inconvenience of becoming a little insulating in very dry air, he preferred employing balls of the same dimensions, but made with a very thin plate of silver gilt. In other respects, the experiments were conducted in the same manner; except that the ball affixed to the insulating stem, and which acts upon the movable ball, is withdrawn from the balance in order to be placed under different conditions which exert an influence, in one direction or the other, over the loss of its electricity; it is then brought back to the balance at the end of a certain time, which is always the same, in order that the loss it has suffered may be determined. The air of the interior of the balance is as dry as possible, so that we may conclude that the loss experienced by the ball of the balance in ten minutes is very small, and always the same for all the experiments.

The following are the results to which this mode of experimenting has lead : —

1st. The loss of electricity by the contact of the air is not increased by the agitation of the air; on the contrary, the loss of electricity in the agitated air is less than that which occurs in the air at rest. This result, singular as it apparently is, is easily explained if we take into account the time which may probably be required, for the particles to become polarised, and thus to transmit the electricity of the body with which they are in contact.

2nd. The loss of electricity that a body experiences, by the contact of the air, is influenced by the bodies that are in its presence, and varies with the electric state of these bodies. Thus the smallest loss occurs, when the electrised body is in presence of a body, which possesses an electricity contrary to its own; it is more considerable when the body in presence is not electrised, and is in communication with the ground, and especially when the two bodies have the same electricity. In order to perform those experiments, the electrised ball, that is withdrawn from the balance, is placed for ten minutes either so that it is insulated in the air, or in presence of an insulated metal sphere, charged sometimes with the same, at other times with

the contrary electricity, or in the centre of a metal sphere in communication with the ground.

The following is the Table of the experiments made in this manner, in air having the same temperature and the same degree of humidity.

Number of the Experiments.	Distance of the Balls.	Torsion of the Micrometer.	After ten Minutes.	Distance of the Balls.	Torsion of the Micrometer.
1	20°	188°	10	20°	105°
2	20	188	10	20	136
3	20	188	10	20	96
4	20	188	10	20	164
5	20	188	10	20	85
6	20	188	10	20	162
7	20	198	10	20	131
8	20	198	10	20	169
9	20	102	10	20	25
10	20	102	10	20	67

We have merely to compare together the results given in the preceding Table, and we shall have the demonstration of this proposition. In the first experiment, the ball was left in the air for ten minutes; and in the second it was placed for the same length of time, in the centre of a hollow sphere of metal, which was in communication with the ground. This sphere was 4 inches in diameter, and the ball was introduced through an aperture of 1 inch. In the third experiment, the ball remained for ten minutes in presence of an insulated metal ball $\frac{3}{4}$ in. in diameter. The centres of the two balls were at a distance of $4\frac{3}{4}$ in. In this experiment, the two balls possessed the same electricity; whilst, in the fourth, the large ball was charged with a contrary electricity to that of the ball of the balance. In the fifth and sixth experiment, the operations were of the same kind as in the third and fourth. In the seventh experiment, the ball of the balance was in the air; whilst in the eighth the ball was in the centre of the metal sphere. In the ninth and tenth experiments, the operations were conducted in the same manner.

3rd. The loss of electricity in pure gases, deprived as

much as possible of aqueous vapours, is independent of its intensity, and is consequently constant, at least for quantities of electricity comprised within certain limits. This law differs from that found by Coulomb, when operating in air more or less moist, and which consisted in this loss, in a given time, being always in the same proportion of the total quantity of electricity. It was by taking every possible precaution to operate in air and in gases, perfectly dried by means of phosphoric acid, and by multiplying the experiments made, either according to Coulomb's method, or according to a method slightly differing, that Matteucci has obtained the loss of electricity in a minute,—that is, in the unity of time. We shall not introduce here the tables of the results, which show that, notwithstanding the differences, that are in every respect small, and that are inevitably due to errors of experiment, the loss of electricity is constant. The experiments were made by means of the two electrised balls, the repulsive force of which was measured, either by bringing them to the same distance, according to the process of Coulomb, or by holding them at a variable distance. In this latter case, the loss is found to be greater, when the distance is less, which agrees with the second law found above.

4th.—The loss of electricity is the same in air, in hydrogen, and in carbonic acid gas, all being very dry, and taken at the same temperature and at the same pressure. The experiments that have led to this result were made at temperatures varying from 46°·4 to 51°·8; days were selected, in which the atmosphere was very dry; a vacuum was made in the globe of the balance, care being taken on each occasion of operating with a new gas, to renew the phosphoric acid, that is placed in it, and then to inject the gas by introducing it very slowly through a Liebig's tube, filled with concentrated sulphuric acid.

5th.—The loss of electricity, which, in dry and pure gases, is in general the same for positive as for negative electricity, becomes more rapid for negative than for positive electricity, when the electric charges are very strong. This important proposition, which had already been pointed out

by Belli, and which confirms other facts relating to discharges, that we shall study presently, is established by a series of experiments, made by electrising the two balls of the balance, sometimes with positive, sometimes with negative electricity. We wait till the movable needle stops at a certain number of degrees, 15° for instance, and the time is then noted by a chronometer; then at the end of a certain time, ten minutes for instance, which is the interval of time between the two observations, the thread is very slowly untwisted through the number of degrees necessary for bringing the needle back to 15°. The following Table shows how much the torsion required to be diminished under the same circumstances for negative as well as for positive electricity; whence it may be concluded, that for comparatively high electric charges, the loss in air was much greater for negative than for positive electricity.

Torsion and Arc of Repulsion.		Torsion and Arc of Repulsion.
Positive Electricity.		Positive Electricity.
140° + 15°		127° + 15°
117 + 15		107 + 15
90 + 15		75 + 15
35 + 15		27 + 15
Negative Electricity.	After Ten Minutes.	Negative Electricity.
140° + 15°		90° + 15°
117 + 15		66 + 15
90 + 15		60 + 15
35 + 15		12 + 15

6th.—The loss of electricity in dry air increases with the temperature. The experiments intended for the establishment of this law can only be made within very restricted limits of temperature, between 32° and 64°·4; for even above 58°, the elevation of temperature diminishes the insulating property of stems of gum-lac itself. However, even within these limits, the influence of temperature over the insulating power of very dry air is very sensible. Thus at 64°·4 the loss of the electricity of the insulated ball was

$\frac{1}{200}$; whilst at 32° it was only $\frac{1}{112}$, that is to say, only the half.

7th.— The loss of electricity in dry air diminishes with the diminution of the density of the air. Thus the divergence of an electroscope in rarefied air, at ·118 inches of pressure, was the same at the end of two days as at the commencement of the experiment; which could not possibly be obtained with air of a greater density. This experiment seems plainly to prove that the electricity escapes by the particles themselves of the air; for, the less there are of them, the less rapid is the escape. We have only to remark that the absolute quantity of electricity that can remain, on the surface of an insulated conducting body, without escaping in the state of tension, is much less when the air is rarefied than when it is under a higher pressure. M. Matteucci concludes from this, that in a perfect vacuum there would be no electricity retained on the surface of the conducting body; we shall see, further on, the extent to which this conclusion may be admitted.

8th.— The loss of electricity in air taken at a constant temperature and pressure, increases with the quantity of vapour of water contained in this air; but not, as Coulomb had imagined, according to a simple law. It is only in air that contains very great quantities of the vapour of water, that the loss is found approximately proportional to the tension or to the quantity of vapour of water, whatever the temperature may be. A very remarkable thing is, that the presence, in very dry air of other vapours, such as those of camphor, of certain essential oils, and even of sulphuric ether, exert no influence over the loss of electricity.

M. Matteucci, in the important work, by which he was led to the results that we have been relating, had endeavoured to determine the influence that may be exerted over the loss of electricity by the nature of the electrised body. Like Coulomb, he had not found any difference in this respect between metal balls or discs, or gum-lac balls or discs; subject, however, to one condition, which is, that gum-lac must be electrised by the spark from a machine; for, if it is electrised by friction, there is a constant difference, which is very

probably due to the electricity, instead of being upon the surface, as in the former case, penetrating more deeply, and consequently not being able to escape so easily.

After having studied the laws of slow propagation, or loss of electricity in gases, let us now turn our attention to those to which is subjected the rapid propagation, that may be brought about, either by discharges, or in a continuous manner under the form of a current.

It is well known that when the conductor, charged with one or other of the two electricities, is terminated in a point, this electricity escapes with facility into the air. This property of points, to which we have already directed attention, is founded upon the great density that electricity acquires at points, in virtue of the laws of its distribution. It may be diminished or even annulled, if the point is placed in the interior of a hollow conductor; for example, if a point, which is fixed upon an insulated and electrised metal disc, is situated in the middle and in the axis of a hollow metal cylinder more elevated than itself, and which itself rests upon the disc. When once the electricity is accumulated at the point, it escapes, and is propagated by determining in the air a very violent mechanical movement, which is probably due to the repulsion exercised by the point upon the particles of air in contact with it, to which it has communicated its electricity. Bodies in combustion, and especially flames, exercise the same effect as points. If, for instance, two metal discs are placed one beneath the other, the lower communicating with the pole of a dry pile, by which it is electrised, and the upper with an electroscope, we have merely to place in the former a fragment of German tinder in a state of incandescence, in order that the electroscope, which is connected with the latter, shall diverge violently. The German tinder therefore, in this case, acts like a point, for its effect, like that of the point, may be annulled, by surrounding it with a hollow cylinder; and this proves that it is not the smoke that carries away the electricity, for it continues to rise as at the first in a thick column towards the upper disc. The influence of incandescent German tinder

is as much felt in discharging the lower disc, as in charging the upper. It acts in an equal degree from above downwards, as from below upwards.

Riess has made a great number of experiments on this subject, by employing a cotton wick, and lighted tapers; but in order to escape from the disturbing influence of the smoke, he found it preferable to employ a preparation of saltpetre and carbon, united together with astringent gum, so as to make tapers of about an inch in length. He has thus proved the influence of conducting envelopes, which prevent the incandescent body from discharging the electricity of the disc upon which it rests, and of charging the disc that is near to it; and he has established in a decided manner, the complete analogy that exists between the mode of action of these bodies and that of points. It is therefore not by means of the products of their combustion, that incandescent bodies exercise their conducting property, but in virtue of the particular state of their surface, which comports itself as if it were covered with very fine points. Moreover, the action of very short, but very perfect points is proved by an old experiment, in which the discharge of an electrised conductor is brought about by presenting to it at a distance a piece of tinder made from the fungus of an oak, without there being even any need of lighting it; which is due to the very fine and almost invisible points, with which the whole surface of this species of tinder is covered. The existence of similar points in a body in combustion is easily proved; they are continuously destroyed and renewed.

In bodies, the combustion of which produce a flame, it is the small filaments of vapour and the points of carbon that conduct the electricity, as may be proved by remarking that the flame does not lose its conducting property by being surrounded by a metal tube, as occurs when the incandescent body loses its electricity by the effect of the points with which it is covered. We may, in a very simple experiment, even see the action of these two conducting portions of the flame succeed each other visibly. If a wax taper, that is burning actively, be suddenly extinguished, the vapour

contained by the flame is seen to act for a few seconds as a conductor, then the wick, impregnated with melted wax, ceases to act; so that the smoke no longer exerts any influence over the electrised body, when brought near to it. But when the wax ceases to reach the wick, the latter becomes incandescent, and then the small points of carbon that are formed there conduct electricity for a brief moment.

The property of bodies in combustion of conducting electricity may serve two important purposes; the first, to remove from an insulating body its electricity, by moving about it a small spirit flame or the point of a lighted taper; the second, to increase the sensibility of an electroscope intended for detecting a distant electricity, by placing upon it a lighted body, which has the power of drawing off electricity at a still greater distance than a point.

In all that we have said in respect to bodies in combustion, we have paid no regard to the nature of the electricity employed: their conductibility is, in fact, the same for both electricities, providing the combustion is active and perfect, and that when German tinder and carbon are employed, the precaution is taken of frequently clearing from them their ashes. If these precautions are not taken, it is frequently perceived that one of the electricities is more easily conducted than the other, which is due to electricity being developed in the very act itself of combustion. It is not until we shall be occupied with the actual sources of electricity that we shall be able to estimate the amount of influence in the conducting power of flames, that may be due to the liberation of electricity, which accompany their production.

When electricity escapes by a point, we have seen that this escape is accompanied by a movement of the air, which is similar to that of a slight breath, and which has been called the electric wind. This wind may be rendered sensible by being directed against the flame of a taper, against the wings of a small mill of paper, which it causes to turn, or against the powder of licopodium placed upon water, which it drives before it. It is to this agitation of the air, or rather to the repulsion exercised by the electric current, which traverses it, upon that of the point whence it escapes

that the rotation, as we have seen, of the electric mill is due. Indeed, in rarefied air this movement does not occur; and we have thus merely to place the mill in the middle of a vessel, whose sides, which are very near to it, are charged with the same electricity as that which is transmitted to it, and the rotation at once ceases. The electric wind favours the cooling and vaporisation of liquids. This had been long ago remarked by several philosophers; but it was Peltier who proved it in a positive manner. With this view, he had placed at a distance of six or seven inches above a platinum vessel filled with water, a ball of metal or bundle of wires terminating in a point. The water having been heated about 156° or 194°, visible vapours commenced arising from the surface, but this cloud of vapour became much more considerable, as soon as electricity from a machine was introduced to the points. A sensitive thermometer, placed in the water, indicated also by its falling an increase in the quantity of vapour formed. The phenomenon was not simply due to the renewal of the air on the surface of the heated liquid: Peltier satisfied himself upon this point, by artificially renewing the air over this surface, by means of a ventilator; the effect was always less considerable than that produced by the electric wind.

The rapid transmission of electricity through imperfect conductors, such as the air, evidently tends to make the particles recede from each other; this is very well seen when the luminous brush, that is composed of diverging filaments, formed of the small particles rendered luminous by the passage of electricity, is studied in the dark. This same tendency is also observed in the case in which the imperfect conductors are liquid. Thus Faraday noticed that by making the electricity, arising from the conductor of an electric machine, pass into sealing-wax, rendered fluid by heat, very fine filaments are detached from it, which cover a piece of paper placed beneath, like fine wool. A drop of gum-water suspended at the extremity of a rod, by which electricity reaches it, resolves itself into detached threads, when plunged into essence of turpentine, itself placed in a vessel, the metal bottom of

which allows of the escape of the electricity. A drop of mercury or of chloride of calcium elongates itself and becomes pointed, and minute drops are detached from it, which are drawn by the electricity into the air, wherein the experiment is made. By employing a drop of gum-water, very various phenomena are observed, according to the force of the electricity that reaches it. At first the drop is transformed into a cone; then, in proportion as the electricity increases in intensity, a part of the liquid is seen to be drawn onward, the rest becomes more pointed and acquires a rugged surface, with the noise peculiar to electric brushes; finally, with a more powerful electrisation, a more considerable portion of the liquid is drawn onward, the remaining drop elongates itself and draws back by fits, forming a very luminous brush. When negative electricity is made to reach the drop of gum-water, the cone that is formed is larger than with positive.

An old experiment, of the same kind as the preceding, and which is due to Nollet, consists in placing water in a metal funnel, furnished with a few capillary openings, and communicating with the electric conductor. The water passes through merely in isolated drops and in a rounded form; whilst, as soon as the funnel is electrised, it comes out in very fine and continuous diverging jets, which are luminous in the dark.

More frequently, instead of occurring in a slow and continuous manner, the rapid propagation of electricity through air and gases, occurs in an instantaneous and sudden manner by discharges. The distance at which this discharge can occur, and which is termed the *explosive distance* or *limit*, for the same intensity of electric discharge, depends upon the density and nature of the aeriform medium. Harris has found, by various experiments, that the quantities of electricity, necessary for traversing a given interval, vary in a simple ratio with the density of the air, and that consequently the explosive limit in rarefied air is inversely as the density of the air; from which it follows that the same discharge can traverse an interval of air of double the length, when the density of the air has been reduced one half. If air contained in a close vessel is heated even to 300°, no variation occurs in

the explosive limit; whilst if the vessel is allowed to be open, it is sensibly increased; which proves that it is not the pressure of the electric fluid, but the number of particles, which is the determining cause of the greater or less difficulty experienced by the electric charge in traversing it. Knockenhauer, by a series of experiments in which, leaving the explosive distance constant, he determined the density of the electricity, necessary for obtaining the electric discharge in different degrees of density of the air, found that these two densities were almost proportional to each other; a result that was also obtained by Masson, by means of a slightly different method.

But of all philosophers, Riess is the one who has made the most conscientious study of this subject. We shall defer to a final note the detailed exposition of the methods and calculations by which Riess succeeded in establishing the laws that regulate the discharge of electric batteries*; we shall confine ourselves for the present to giving the formula, by which he expressses the value of the explosive limit. This formula is $d = b\frac{q}{s}$, b being the explosive distance for the charge taken as unity, d, the explosive distance for the quantity q, of electricity, and s, the size of the surface of the battery, upon which the electricity is accumulated, or the number of jars, of which the battery is composed. In order to demonstrate by experiment the accuracy of the formula, Riess employs an apparatus, which he named *spark-micrometer*; and which consists (*Fig.* 185.) of two vertical insulated metal rods, each terminated by a ball; one of the rods is fixed, the other is moved by means of a micrometer screw, which allows of the exact measurement of the distance, to which the two balls must be brought in respect of each other, in order that the discharge shall occur between them.

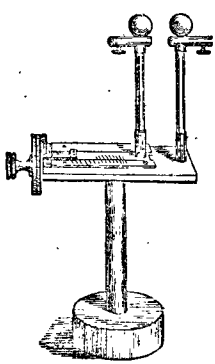


Fig. 185.

* Vide the final note C.

One of the balls of the instrument communicates by a wire with the inner, the other with the outer coating, which is also put in communication with an electrometer. In a first experiment, the balls of the micrometer were at a distance $d = \frac{1}{2}\,1$; that is, the distance 1 in the following Table; the battery composed of s jars was charged until the discharge occurred, and the electrometer indicated the value of the quantity q, of the electricity employed. The value of the constant b, was thus found, which gave $q = 0{\cdot}833\ s\,d$. Now, the following Table gives for the different values of d, and s, the corresponding values of q, observed directly and calculated according to this formula.

d	2 s.		3 s.		4 s.		5 s.	
	q. Obs.	q. Calc.	q. Obs.	q. Calc.	q. Obs.	q. Calc.	q. Obs.	q. Calc.
1	„	„	3·0	2·25	3·5	3·3	4·3	4·2
2	3·	3·3	5·5	5·0	7·0	6·7	8·5	8·3
3	4·6	5·0	7·0	7 5	10·1	10·0	12·5	12·5
4	6·4	6·7	10·3	10·0	13·5	13·3	16·0	16·7
5	7·5	8·3	„	„	16·0	16·7	„	„

The agreement of calculation with observation very well shows the accuracy of the formula. It is evident that, when once the constant b is given and without recourse to the electrometer, we are able to determine very exactly, by means of this formula, the quantity of electricity, with which the battery is charged, provided we know the number of jars or the surface s, of the battery, and the striking distance d, furnished by the spark-micrometer.

Experiments, made with different gases, had shown Doeberainer that the explosive distance is less in proportion as the gas itself possesses greater density. Schaffautl had found, in hydrogen compressed and heated to 536° in a close vessel, that this distance was greater than in ordinary air, the pressure of which however was twenty-seven times less.

These differences between the various gases had already been pointed out by Morgan at the end of the last century.

He had remarked the relation that exists between the explosive distance and the charge of the battery; and that, for a given charge, hydrogen furnishes the greatest explosive distance, and muriatic acid gas the least. Faraday, not very long ago, took up the study that had been touched upon by Morgan: his method, without being rigorous, led to approximate results, which, if they do not present a mathematical precision, at least enable us to classify the different gases into the order of their permeability by the electric discharge. The conductor of an electrical machine must be put into communication with an apparatus, consisting of two metal balls, between which the spark must pass, when traversing ordinary air, and at the same time with a similar apparatus placed in the interior of a receiver, in which a vacuum can be made, and into which various gases can be introduced (*Fig.* 186.). The two balls of the apparatus, that are placed

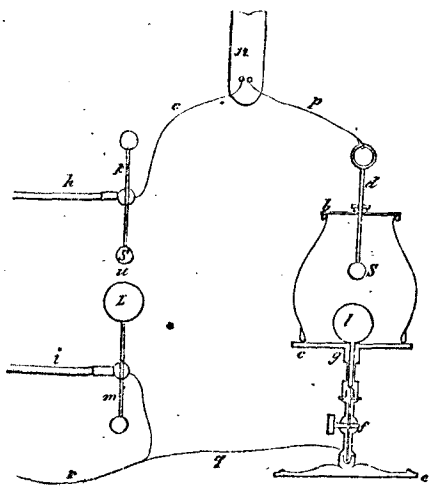


Fig. 186.

within the receiver, are at a constant distance of 0·62 in. from each other, whilst the mutual distance of the two balls that are placed in the air, can be diminished or increased, so that the electric spark passes by one or other of the two paths that are open to it, or is divided equally between them.

Faraday, by introducing the gases successively into the receiver, determined for each what was the smallest distance at which the two balls that are situated in the air, could be placed in respect of each other, in order that the spark should still prefer to traverse the gas, and not the air; and also the greatest distance that could be given to them without the spark ceasing to pass through the air, in preference to the gas. Between these two distances, the spark must divide itself between the air and the gas; by taking the mean of this, we obtain for each gas the value of the explosive distance in the air, equivalent to that of the gas; which is always at 0·62 in. Since, on the other hand, the quantities of electricity, that pass in the air between the balls, are proportional to the distances of these balls, we are enabled to discover, by means of these distances, the quantity of electricity that is necessary, in order to traverse the same explosive distance in each gas. By this process it is found that, under the same pressure and at the same temperature, this quantity is greatest for hydrochloric acid gas, and least for hydrogen; so that with the same quantity of electricity, the spark would be longest in hydrogen, and shortest in hydrochloric acid gas,—a result in conformity with what had been discovered by Morgan.

The gases, that were subjected to experiment, had all been carefully dried, and were all at the same temperature and under the atmospheric pressure. The following is, for instance, a table in which at the side of each gas is indicated the mean explosive distance of the two balls in air, equivalent to the constant explosive distance of the gases.*

Hydrochloric acid	1·105
Olefiant gas	0·750
Ordinary air	0·695 †

* The distances are expressed in inches and fractions of an inch, and the constant distance of the two balls in the receivers, into which the gases were successively introduced, was 0·62 in.

† It does not appear to me that this result can be admitted; for the explosive distance for air in the receivers should be equal to that of air out of the receivers, namely, 0·62 in.; for it is the same air under the same pressure and the same temperature.

Carbonic acid gas	0·640
Nitrogen	0·615
Oxygen	0·505
Oil gas	0·490
Hydrogen	0·370

In Faraday's experiments, the two balls that are put into communication with the conductor of the electrical machine, and placed one in the gas and the other in the air, were of the same size, but had a diameter of about one-half less than that of their two corresponding balls, that were in communication with the ground. It followed from this, that if the conductor of the machine were charged with negative instead of being with positive electricity, as in the above experiments, the explosive distances in the air, equivalent to those of each of the gases, were all a little less; but the order of the gases was not altered by the change, except that the difference between hydrochloric acid and olefiant gas became almost null.

The experiments that we have described, as Faraday himself has remarked, are far from possessing the accuracy that would be necessary before any great importance could be attached to the numbers of the above Table; for unexpected circumstances very frequently cause them to vary through very considerable limits; thus a little dust, a little more or a little less moisture in the air, would modify the direction and the length of the spark, under conditions apparently the same. Nevertheless, these two important facts are deduced from the inspection of the Table: — the first is that, under the same pressure, and at the same temperature, the various gases require different changes of electricity, in order to be traversed by the spark through a path of the same length; the second, that these differences are not simply due to the density of the gas, but also to its nature; since olefiant gas, less dense than oxygen, and especially than carbonic acid, requires a stronger charge. We have only to regret that the difference of the diameter of the balls has introduced an extraneous element into the study itself of the phenomenon, which is thus found to be a little complex.

We see, from what has gone before, that, as far as the propagation of electricity in gases is concerned, a distinction must be made between the case of slow propagation or loss, and that of rapid propagation or discharge. In the former case, indeed, the density of the gas or the number of its particles, is a circumstance favourable to the propagation; and the nature of the gas has little or no influence. In the latter, the density of the gas, on the contrary, is an unfavourable circumstance, and the nature of the gas has a very decided influence. Moreover, in the latter case there is a movement, an agitation in the air, which indicates that its displacement is necessary to the propagation; and that consequently, far from facilitating, its presence opposes it. The same things happen when rapid propagation occurs under the form of a continuous current, instead of being brought about by discharges. M. Colladon and myself have satisfied ourselves upon this point, by causing static electricity accumulated and constantly restored upon an insulated conductor, to pass in the form of a current, according to the plan contrived by M. Colladon himself*, through common air, taken at different state of density, temperature, and humidity. We employed a glass globe about 9 in. in diameter, fitted up with two necks, in the same diameter. We passed through one of the necks an insulated metal rod, terminated in the interior of the globe by a platinum ball, and communicating exteriorly with the electrised conductor; the other neck was traversed by a similar rod, but terminated interiorly by a platinum point maintained at about $\frac{1}{2}$ in. distance from the ball, and extending exteriorly to one end of the well-insulated wire of a galvanometer, the other end of which was in communication with the ground. By operating carefully we were satisfied that in air rarefied to $\frac{1}{25}$ or $\frac{1}{12}$ in., the needle of the galvanometer experienced as strong a deviation when the platinum point and ball were at a distance of 2 in. as when they were in contact with each other; the deviation was 55° in both cases, whilst

* Vol. I. p. 328.

it was only 35° in air under the pressure of 28·29 in. In another experiment, the air having been rarefied and heated to 122°, the deviation was 57°, whilst it was only 24° with air under the pressure of 28·7 in., at the same temperature. The distance of the ball and point in this case was 5 in. If the interior of the globe was saturated with aqueous vapour the air in it being very rarefied, the transmission of electricity occurred less easily in it than in very rarefied but dry air. In fact, the globe being heated as before to 86°, a deviation of 55° was obtained, the point and the ball being at a distance of 2 in., and 60°, when they were in contact; whilst in very rarefied air, heated but dry, the deviation was exactly the same, whether the ball and point were in contact or not.

M. E. Becquerel obtained much more complete and remarkable results, by transmitting the current of one or more pairs through different gases. His apparatus consisted of a platinum tube, drawn through the draw-plate and without any soldering, 25½ in. in length, and $\frac{2}{3}$ in. in internal diameter, sufficiently thick for a vacuum to be made within it without its being compressed out of shape, even when a portion of its length was raised to a red-white temperature. The tube passed through a furnace, and was so arranged that it could be brought to a red heat along an extent of 7½ in. It was terminated at its two extremities by plugs containing glass tubes, which allowed of the introduction into the platinum tube of various gases, and of their being rarefied by means of the air-pump. A platinum wire, that traversed one of the plugs, served as one electrode, the tube itself serving as the other electrode. In some cases, M. E. Becquerel used for electrodes insulated platinum wires, which passed without touching each other, in the middle of a porcelain tube heated to redness. Every precaution was taken that the supports and the various adjustments should not be exposed to variations of temperature, which might have modified their insulating power, so that the gas alone and the electrodes were subjected to these variations in these different experiments. The experiments were made

by passing the current, produced by one or more of Grove's pairs, along the wire of a sensitive galvanometer, and through the gas placed in the tube. The circuit also contained a rheostat, consisting of a liquid column of very small diameter, which might be lengthened or shortened by thrusting a platinum wire, that serves as an electrode, to a greater or less depth into a graduated tube, in which the column is contained; this liquid was distilled water holding in solution variable proportions of sulphate of copper, according to the experiments, and the other electrode was a plate of metal placed at the base of the column, and in communication with it. When wishing to operate, we begin, by removing from the circuit the gas that is the subject of experiment, and giving to the liquid column of the rheostat such a length that the needle of the galvanometer should be deflected to 20°, for instance; then, without changing anything, the gas was replaced into the circuit, and the end of the platinum wire of the rheostat was lowered until, by diminishing the resistance of the liquid column, as much as that of the circuit had been increased by the introduction of the gas, the deflection of the needle was brought back to what it had been, namely to 20°. The intensity of the current evidently remaining constant, the length of the liquid column, comprised between the two portions of the extremity of the platinum wire, was equivalent to the resistance of gas contained in the tube, increased by the resistance to passage of the two electrodes, that transmitted the current into the gas.

By means of this apparatus, M. E. Becquerel has established several important facts. He first satisfied himself, that the propagation of the current through the gas could not take place before the latter had attained to red-heat; but that, setting out from this point, the resistance of the gas diminished progressively, in proportion as the temperature was raised; and that this diminution was very rapid, when the tube was strongly heated to red-white. All gases present the same property, although in different degrees. When the tube and wire are used for transmitting the current

into the gas, it is found that the transmission is more easy when the tube, that is to say, the more extended electrode, is negative, and the wire positive, than in the converse case.* With two parallel and insulated platinum wires for electrodes, there is no difference; and the transmission occurs with an equal facility, whether the current goes in one direction or in the other. On employing these two wires, placed at $\frac{1}{10}$ in. from each other, it is found that *the resistance of air heated to redness, is thirty thousand times greater than that of water, containing $\frac{1}{2}$ a ten-thousandth part of sulphate of copper in solution.* This resistance includes that which is due to the passage of the electricity from the electrodes into the gas, independently of that due to the passage through the gas itself.

In order to prove the influence of the elastic force of gases upon their resistance to the passage of electricity, we have merely to rarefy the air or gas contained in the platinum tube, taking care to maintain the tube at red-heat. The following is the result of an experiment, made with the current of a single pair, transmitted through air maintained at red-heat, but gradually rarefied to the pressure of ·078 in. of mercury; the needle of the galvanometer was brought back to the constant deflection of 25°, by means of the rheostat.

Elastic force.	Resistance.
Ordinary Pressure.	20·9
5·38	7·1
1·59	4·8
·078	3·8

Even in the case of the greatest rarefaction, there still exists a very appreciable resistance between the two platinum electrodes, which is superior to $\frac{1}{10}$ of the resistance, presented

* Mr. Andrews, in studying the conducting power of flames and heated air for electricity, had already found that air, heated to redness by an Argand lamp, conducted the current of a pole of twenty pairs, only when the positive pole was in communication with the platinum wire, placed within the heated air, and the negative with the brass tube of the lamp, near the orifice from which the flame came out; in the converse case, the current did not pass; the transmission of the current was detected by means of the decomposition of iodide of potassium.

by heated air, at the same temperature and the ordinary pressure.

A fact, worthy of especial notice, is that the temperature, at which a gas begins to transmit the voltaic current is the same, whether the gas is rarefied or maintained at the ordinary pressure; it requires as elevated a temperature in the one as in the other case; but, when once this temperature is attained, which is that of nascent red, the differences become sensible with the variations of pressure.

The gases may be classified as follows, into the order of the resistance they present to the current at red-white temperature, under the pressure of the atmosphere, the electrodes being of platinum, and the resistance of the air being taken as unity: —

Hydrogen (resistance comprised between 0·3 and 0·4).
Proto-carbonated hydrogen.
Oxygen (resistance comprised between 0·4 and 0·7).
Chlorine (resistance not exceeding 0·9).
Protoxide of nitrogen, and nitrogen (resistance very different from that of air).
Carbonic acid (resistance comprised between 1·2 and 2).
Vapour of water (resistance greater than the air).

Heat, like rarefaction, acts upon all gases so as to diminish their resistance to the transmission of electricity, but this diminution is not equal for all; in proportion as they are heated and rarefied, the relations that express their resistance to the passage of the current, unceasingly tend to approximate to unity. When the pressure of about $\frac{1}{10}$ in. of mercury is attained, all gaseous substances transmit the current equally well, provided their temperature is the same. Heat acts in the same direction as diminution of pressure; but it possesses manifestly an action peculiar to itself, since at the ordinary temperature, in the most perfect vacuum that can be produced, there is no appreciable transmission of electricity, whilst at red-heat, electricity is able to traverse a gas, even when it is not rarefied.

The resistance presented by gases, under their different conditions of temperature and rarefaction, to the transmission of electricity, varies with the number of pairs and with the

intensity of the current, produced by the same number of pairs. The study that M. E. Becquerel has made of these anomalies, would seem to demonstrate that they are due to resistances, experienced by the current in passing from the electrodes into the gases, which are variable, according to its intensity.

M. E. Becquerel's experiments are of a nature to confirm the remark that we have already made, upon the difference existing in the action of gaseous substances, between the case of slow loss and that of rapid propagation of electricity. We even see that the influence of the density and of the nature of the gas is almost the same, whether the rapid propagation occurs by discharge or by current; with regard to that of temperature, it has not been studied in the case of discharges; it is very probable that it would lead to results, analogous to those which have been obtained for the case of currents.

It appears to us, therefore, to follow, from all this collection of researches, that the function of air and of gases is exclusively negative, in connection with the rapid propagation of electricity; whilst it is positive when slow propagation or loss is in question. In this latter case, the particles of the gas are polarised by the electricity of the body that is placed in the midst of them; and they discharge the body, and discharge each other successively, more or less slowly, according to certain circumstances, in the same manner as takes place with particles of imperfect conductors, whether solid or liquid. Thus the conditions of the phenomenon are the same, whether the bodies, by means of which the slow loss is brought about, are gaseous, liquid, or solid. It is, however, possible that in gaseous bodies, the propagation of electricity is brought about by a slight movement or displacement of the particles, as occurs in the propagation of heat.

If the propagation is rapid, the tendency of the two electricities to unite is opposed by the presence of the insulating particles, whether the medium be gaseous, solid or liquid. This reunion, that is to say, the discharge or current, can take place therefore only when the particles are separated; hence the breaking of solid bodies, the

movement and agitation of the particles in liquids and in gases; hence also the differences between different substances in regard to their facility of allowing the discharge to pass; the gases, whose particles are more mobile, allow it more readily to pass, and among them there are also differences due to their difference of mobility, which is not in relation with their specific gravity. The influence of rarefaction becomes no less easy of comprehension, when the particle of gas is no longer a more or less imperfect conductor, but an obstacle to the transmission of electricity. Finally, the effect of temperature is equally explicable, if we confine our attention to considering it in the solid electrodes, charged with the contrary electricities, and not in the gases, where it may be considered as null, since it is the same whether the gas be at its ordinary density, or be rarefied so as not to counterbalance more than ·078 in. of mercury.

An important fact, that must also be referred to, before leaving the subject of the propagation of electricity in gases, is the difference existing between positive and negative electricity, with regard to their respective facility of bringing about discharges, under similar circumstances. We have directed attention to this difference, as far as concerns slow propagation, when relating Matteucci's experiments. Belli had, however, before Matteucci, observed that, for equal tensions, negative electricity dissipates itself more promptly than positive, the state of the atmosphere and the arrangement of the apparatus being exactly the same; he operated by means of a quadrant electrometer, the balls of which took 10′ 2″ to descend from 200° to 10°, when they were charged with positive electricity, and only 4′ 30″, when charged with negative. With regard to rapid transmission or discharge, we have long been acquainted with the remarkable difference presented by the light, which accompanies it in the form of a spark, according as the electrised surface, from which it proceeds is positive or negative. But, independently of this appearance, which we shall study when directing our attention to the electric light, there is a more general fact established by Faraday, concerning the discharge itself.

We remark, first, that, when the discharge occurs through air, between two balls of unequal size, the spark is much longer when the smaller of the balls is the positive, and the larger the negative, than in the reverse case: thus, in the former case, it could attain to eight or twelve inches in length, and in the latter to ·8 or 1·2. There is also an important difference in the length of the spark, according as the balls receive the electricity directly from the source, that is to say are *inducteous*, or as they receive it by induction, that is to say are *induced*. Thus the spark is twice as long, when the smaller ball is rendered positive directly, as it is when it is so by induction; an analogous difference, although not so great in amount, may be observed, when the ball is negative instead of positive.

In order fairly to determine the different degrees of tension or electric charge, that are acquired by the small balls, before the discharge occurs, according as they are positive or negative, the following apparatus (*fig.* 187.), may be employed, consisting of two metal forks, L and R, each terminated by balls of different diameters; the balls A and D, are two inches in diameter, and the balls B and C, 0·2 in.; the distance between each of the large and small balls on the same fork is about ·94 inches; the two forks being movable, the intervals *n* and *o*, may be varied; one of the forks is placed in com-

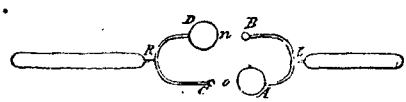


Fig. 187.

munication with the source of electricity, and the other with the ground. The intervals *n* and *o*, being each one inch, and the balls A and B, being positive and inducteous, the discharge occurs at *n*, and more frequently with a brush; the same balls being still inducteous, but negative, the discharge still occurs at *n*, but always with a brush. Here the advantage is in favour of the small inducing ball, whether it be positive or negative; but if the interval *n* is made ·86 in., and the interval ·62 in., the discharge also occurs between the two inter-

vals, when A and B are inducteous and positive; when they are negative, the discharge occurs in greater proportion at *n*, which seems to prove that the small ball discharges itself more easily when it is negative than when positive. This experiment, and others of the same kind, led Faraday to admit that, of two equally conducting surfaces, placed in air, and electrised to the same degree, the one that is negative discharges itself at a little lower tension than does the one that is positive; and that, when the discharge occurs, it passes in stronger proportion from the positive to the negative surface, than from the negative to the positive.

These different effects are very probably due to the nature of the interposed dielectric body, which is in this instance common air, and to the manner in which its particles are polarised; what proves this is that they vary with the gases, that are placed in the course of the discharge. Faraday, in order to study the influence of different gases, arranged the apparatus of *Fig.* 187. so that the two forks might be in a receiver, into which the gas was introduced, and that each pair of balls might be in communication exteriorly to the receiver, as in *Fig.* 186., either with a source of electricity or with the ground. Upon operating in the same manner as with air,—namely, by rendering A and B, sometimes positive inductors, at other times negative inductors—it is found that the small *negative* ball has a decided superiority over the *positive* ball, for determining the discharge in olefiant and in carbonic acid gas, whilst in nitrogen and hydrogen it is the reverse.

The phenomena upon which our attention has been engaged, are therefore intimately connected with the manner in which the propagation of electricity occurs in elastic fluids, and consequently with the effects that accompany their propagation; we shall also have occasion to return to this in the following Chapters, which are devoted to the study of these effects. They are to be traced to the same cause, to which the differences observed by M. E. Becquerel in the facility of the transmission of the electric current through gases are due, according as the positive electricity arrives by the pla-

tinum wire or tube. Finally, when we are studying the phenomena of decomposition, that accompany the passage of dynamic electricity through liquids, we shall see effects of the movement and transport of the liquids themselves, from the positive to the negative pole, which further indicate a disparity in the mode of action of the two electricities.

General considerations on the mode of the transmission of electricity, in bodies and in vacuo; and on certain molecular phenomena, that are its result.

The study, that we have made of the propagation of electricity through solid, liquid, and gaseous bodies, and through good, and also imperfect conductors, naturally leads us to distinguish two modes of transmission. The first occurs by the intervention of bodies, from molecules to molecules, and more or less rapidly, according to the degree of conductibility of these bodies and molecules; this is what, with Faraday, we have called *conduction*, and which is always accompanied by molecular induction. All bodies may therefore be considered as conductors; those which we call insulators being merely conductors to so feeble a degree, that they do not permit of a propagation of electricity of sufficient rapidity to admit of the production of a current; there is merely slow loss. The mode of transmission by conduction may be attended by calorific and chemical effects; in the latter case, it constitutes the mode by *electrolysis*, which is only a particular case, but which Faraday, however, regards as a distinct mode. The second mode occurs at a distance; it is the result of the tendency that is possessed by the two electricities of uniting by virtue of their mutual attraction; and it is brought about the more easily, in proportion as the medium, necessarily an insulator, that is interposed between the two solid conductors, the positive and the negative, contains a smaller number of material particles. The most favourable medium, therefore, for this mode would be a perfect vacuum; and all experiments seem to demonstrate this. But it by no means follows from this that vacuum is a conductor; for

conductibility supposes a succession of material particles, by which the electricity is propagated; but we are here discussing the transmission to a distance, without the intervention of contiguous particles. Vacuum, therefore, in this case plays merely a negative part, that is to say, it is the condition of space, most favourable to the reunion of the two electricities at a distance, because it contains no matter that is opposed to this; but it does not itself conduct, as we are about to prove.

How is this reunion of the electricities from a distance brought about? Is it simply through the ether, and by its intervention? or does it always occur by the intervention of very fine particles, detached from the electrodes, charged with the contrary electricities and transported from one to the other? Faraday equally admits the two modes: he calls the former *disruptive* discharge, because it is brought about by the violent displacement of the particles of the ambient medium, producing light under different forms; and the latter he calls discharge by *convection* or transport, because the discharge occurs by means of particles transported, differing from conduction, in which the material particles undergo no sensible movement. I should be disposed to believe that these two modes constitute but one, and that even in the cases where the discharge is least violent, there occurs on the small scale what is found on the large in the phenomena of the voltaic arc, namely, a true transport of very finely divided molecules. All the conditions, such as the heating of the electrodes, the rarefaction of gaseous media, that favour transmission, are of a nature to facilitate disintegration by electricity, and the transport of small particles appertaining to the electrodes. It is true that it seems difficult to conceive that the electricity of a single pair is able, as M. Becquerel has remarked, to have sufficient intensity to be transmitted in this manner; but this objection is not peremptory; for we shall see many other examples, in which the electricity of a single pair is able, when circumstances are favourable, to produce effects that commonly require a pile of many pairs. But, in M. Becquerel's experiments, the high temperature to which the electrodes are

brought, and their great approximation, must singularly facilitate the production of the effect that we have been pointing out. Further, we cannot conveniently treat the important question that we have raised, until we are in the Chapters, in which we shall be occupied with the calorific and luminous effects of electricity; we shall then be able to examine whether we must admit that the two electricities are able to unite at a distance, without the intervention of material particles, or whether this reunion always requires necessarily the presence, either of continuous matter, which constitute conduction, or of particles, transported between two bodies, charged with the contrary electrisation, which would reduce the different modes of discharge to two alone. And it would even not be impossible for these two modes not essentially to differ from each other. In fact, what is conduction, if it is not a succession of discharges that occur from molecules to molecules, at infinitely small distances, instead of being brought about between bodies of certain dimensions, at distances of finite extent? Moreover, in conduction, the discharge occurs through molecular vacuum, and consequently, whether on account of this circumstance, or of the small distances by which the molecules are separated, it is not necessary that the electricity should possess any great intensity, in order that it may be transmitted. We may also simply ask if the molecular discharges occur, merely by the intervention of the interposed ether, or if there is a very minute transport of matter from one particle to another? This question, which is precisely the same as the one that we have raised for discharges that are brought about at finite distances, cannot be suitably discussed, until we are studying the effects that are produced upon bodies by the passage of electricity. However, we may even in this place remark that the molecular alteration, experienced by solid conductors, that have served a long time for the transmission of the current, and which has been pointed out by M. Peltier; and the chemical decompositions, that accompany this transmission in liquids, would rather seem favourable to the idea of atomic and molecular movement.

Thus then, to sum up. There might be only one mode of propagation of dynamic electricity, namely, by discharges, occurring either from molecules to molecules, or at distances infinitely small, or from bodies to bodies at finite distances, succeeding each other, sometimes in a manner sufficiently rapid to constitute the current, sometimes too slowly to assume this form. The only question that would remain for solution would be to ascertain whether these discharges always occur by the intervention of material particles, or whether they can equally occur by the intervention of the ether, and without the presence of ponderable substances. This is the question that we shall be called upon to examine in the subsequent Chapters of this Fourth Part, when we shall be engaged with the effects of the propagation of electricity, after having confined ourselves in the present Chapter to prosecuting a general study, that shall be as complete as possible, of this propagation itself.

We have now to give direct proofs of the non-conductibility of vacuum, that we have admitted in what has gone before. These proofs are very difficult to obtain, because it is impossible to deprive space entirely of all ponderable matter; there always remains in the vacuum of the air-pump, and even in the barometric vacuum, a certain quantity of vapours. However, by filling with mercury that has been well boiled, a tube closed at one end, and which is plunged by its open part into a cup, also filled with mercury, we are enabled to obtain at the top of the tube a very empty space, by rarefying the air above the mercury of the cup, which causes the column of mercury contained in the tube to descend. By surrounding the empty part of the tube with a metallic coating, and electrising it as if it were a Leyden jar, Morgan first saw the electric light in the interior; and which seemed to prove that vacuum was a conductor, and that it conducted like an inner coating. But by taking the precaution thoroughly to dry the mercury and the tube, he no longer obtained any effect; and he was able to prove that, on electrising the exterior envelope, no trace of electricity was developed in the interior. Erman, after having inserted a

platinum wire in the top of a barometric tube, and having made in it as perfect a vacuum as possible, by having the mercury well boiled, satisfied himself, by means of an electroscope, placed in communication with the insulated mercury of the barometric reservoir, that electricity which he caused to enter the platinum wire, did not arrive at the electroscope, and, consequently, did not traverse the empty space 6¼ in. in length, comprised between this wire and the top of the column of mercury. Davy, on his part, had proved, by means of a small electroscope, attached to a platinum wire, which itself was fixed, as in the preceding experiment, at the top of a tube empty of air, and resting by its base on mercury, that the balls of this electroscope diverged, when the end of the platinum wire, with which they were in communication, was electrised exteriorly. This divergence, however, would not have taken place, if the electricity had been able to propagate itself through empty space. We have already seen * that Harris and Becquerel have also maintained for several days, the divergence of the gold leaves of an electroscope, by placing it under a receiver, in which the air had been rarefied as much as was possible, by means of the air-pump. Riess made the same observation; he even remarked that the divergence of an electroscope, which had descended from ·51 in. to ·35 in., at the end of 55 minutes in the air of a receiver, remained the same, namely, at ·51 in. for 68 minutes, when the air had been rarefied, until it could support only ·39 in. of mercury. It is merely necessary, in order to the maintenance of this divergence, that the electrised body placed in the vacuum, should be at a sufficiently great distance from every conducting body communicating with the ground; otherwise the electricity is dissipated, and a bluish light is perceived between the electrised body and the neighbouring conductor.

We may, therefore, admit that an electrised body, surrounded on every side by a perfect vacuum, would always preserve its electricity, provided it was at a sufficient distance

* Vol. I. p. 131.

from every other body, so that it could not discharge upon it,—a distance necessarily dependent upon the intensity of its electricity. It follows from this that electricity remains upon the surface of conducting bodies, so long as it is not carried away by the contact of particles, that are more or less conductors, or by the attraction exercised upon it by the contrary electricity of a neighbouring body. We here find a confirmation of the objections that we had raised against the property, that had long been attributed to atmospheric pressure,—regarding it as the cause that maintains electricity upon the surface of conducting bodies.

Before terminating this paragraph, we have still to speak of certain phenomena that are connected with this action, by virtue of which, electricity, in propagating itself, and probably in order to propagate itself, displaces, disaggregates, and frequently transports the particles of bodies; in a word, alters their molecular state. These phenomena are numerous and various; and, although they almost always accompany the other effects of the transmission of electricity through bodies, they must be studied in a distinct manner, because they are to a certain extent independent of it, and are sometimes distinct from it, and because they are connected in a more intimate manner with the very mode of the propagation of this agent.

M. Fusinieri has proved in an evident manner, by a great number of experiments, the transport of metallic molecules that takes place from one conductor to another, when the discharge of a Leyden jar, or even the simple spark of an electrical machine, is made to pass between these two conductors. Thus, particles of silver are transported upon copper, and are even able to penetrate it; and reciprocally, copper is transported upon silver. Among the experiments, which prove that disaggregated metallic particles are able, under the influence of the electric discharge, to penetrate another metal, without being arrested by it, we will cite the following. A disc of silver, well cleaned, of the thickness of a sheet of cardboard, and about $3\frac{1}{2}$ in. in diameter, is placed in contact by its centre with a gold ball ·58 in. in diameter,

which itself communicates with one of the coatings of a battery composed of two large Leyden jars; the other coating communicates with a silver ball, which is brought near enough to the disc for a spark to pass between them. When several discharges have been made to pass in this way, a beautiful spot of gold, or a very thin plate of this metal, is observed upon the surface of the silver disc, from which the spark proceeded, the formation of which requires that gold shall have traversed the silver, without having mixed with it: on the other surface of the silver, and precisely at its point of contact with the gold, a small circular cavity is found, which seems to present certain traces of fusion. We also observe that silver has been transported upon the gold; but it does not extend so well as the gold, which is of all metals the one that forms the largest, and, consequently, the thinnest spot, probably on account of its great ductility.

But the most remarkable effects of this kind are those observed by Karsten, and by several other philosophers, and designated by the name of electric figures or images. They must not be confounded with the figures or designs, that may be formed by electrising certain points of insulating plates, and then powdering them with certain powders or dusts, which reproduce the figures that had been traced with electricity. Such are M. Lichtenberg's figures in which the powder itself is electrised, which makes the images come out better, and enables us to distinguish those that are traced with positive, and those that are traced with negative electricity. Such are also the figures that are obtained by covering a plate with a non-electrised insulating powder, and moving normally over the plate the point of a metal rod, held in communication with the knob of a charged Leyden jar. In this manner, a portion of the electricity passes to the plate, another to the powder, so that the marks designed by the point and the powder are similarly electrised, and the figure is thus traced by lines, from which the powder is cleared away. It is by this means that Wiedemann, as we have seen *, proved the difference of conductibility, presented

* Vol. II. p. 132.

by certain crystals, according as electricity is propagated in one direction or another. These figures also furnish very characteristic differences between positive and negative electricity; and we shall return to this, when we are studying these differences, and are occupied with the electric light. For the present our attention is to be occupied with electric images of another kind, namely with those that are due, not to a simple attraction, exercised upon pulverulent substances, by electricity that remains adhering, according to certain directions, to insulating plates, but to a permanent molecular modification, produced in conducting bodies, as well as in non-conductors, by the effect of the passage of the electricity.

Moser had discovered in 1842, the remarkable fact that, if two bodies are in contact, or very near together, they impress their image upon each other. Thus we have merely to place a medal or a piece of money upon a highly polished metal plate, and to leave it there for some time (about twenty minutes), in order that this plate may preserve the impression of the medal or the piece of money. The effect, in this case, is not very marked, but it becomes much more sensible, if the plate is exposed to the vapour of mercury or to the vapour of water, such as is produced by the breath, these vapours condensing themselves, so as clearly to designate the outlines of the image. If the plate is of silver and has been iodised, a much more distinct image is obtained. What is remarkable is, that these experiments succeed as well in perfect darkness, and during the night, as under the influence of light. So that Moser had attributed this class of phenomena to a peculiar action of the most refrangible dark rays, setting out from the principle that all bodies radiate light, even in complete darkness; and he considered this action to consist in modifying the substances in such a manner that, after having been subjected to it, they condense various vapours, otherwise than they would but for this; the discovery of Daguerre being only a particular case of this general action.

Karsten succeeded, a short time after Moser's discovery, in producing similar figures, under analogous circumstances, making use of electricity. He placed a piece of money on a

glass plate, which was itself resting upon a plate of metal; he then passed some electric sparks upon the money, which were discharged upon the metal plate, by passing round the glass plate. At the end of a hundred turns of the electrical machine, the piece of money was removed, and on breathing upon the glass plate, which had apparently suffered no alteration, the entire impression of the piece was seen to reappear with its most minute details. By employing thin plates of glass, a great number may be superposed upon each other, and we then obtain figures of the medal upon each of them,— feeble it is true, and which become less and less distinct; but which are, however, always to be recognised. In general, the figure is more defined, in proportion as the species of Leyden jar, formed by the association of the medal and the metal plate, discharges itself more frequently and in a spontaneous and continuous manner, so as to produce as it were a glory radiating around the piece of money.

The effect that we have been describing is in no way due to traces of electricity remaining adhering to the glass plate, after the spark has been passed. This may be easily proved by rubbing the plate with a piece of stuff, or by leaving it exposed for some time to the air, which causes all the electricity to disappear; and yet the figure remains with the same distinctness; it is even a matter of some difficulty to cause it to disappear, by heating and then blowing upon it. But the strongest proof is, that the same figure may be reproduced upon plates of polished metal, a case in which it is impossible to admit that there is any electricity adhering. In order to succeed well, the electricity must be prevented passing too rapidly from the piece of money to the metal plate, that is to receive the impression of it; and for this purpose, it is necessary, instead of placing them immediately in contact, to separate them by a thin plate of glass, or which is better still, by a thin plate of mica. We thus obtain readily, after fifteen or twenty turns of the plate of the machine, or in ten or fifteen seconds, a figure of extraordinary distinctness. The thinner the body is, and consequently, the more perfectly the two contrary electricities are disguised,

the greater is the distinctness as well as the rapidity with which the figure is formed. We may vary the nature of the plate, that is intended to receive the images, as well as the objects themselves, whose figures we desire to obtain. Karsten employed indifferently coins and medals, of various metals, seals, engraved stones, &c.; however, the most decided results, are those that are obtained with various pieces of coin, on account of the uniformity of the impression. With regard to the plates, the best conducting bodies are the best: and, when using a plate of silver, similar to that which is used for daguerreotype, there is obtained upon this plate, after a considerable number of turns of the machine, a very visible impression of the medal and of the sheet of mica, even without there being any necessity of causing them to appear by means of vapours. After a thousand turns of the machine, the entire figure was produced upon the plate, as if it had been done by aquafortis; and it presented a brownish colour.

The phenomena observed by Karsten have a great resemblance to those discovered by Moser, although they are produced in a very different manner. The modifications experienced by the surfaces that receive the impression of medals and of other objects, appear in both cases to be of the same nature; but what this nature is, is the question that presents itself.

Riess had already remarked, before Karsten's experiments, that figures may be produced upon plates of glass and mica, by means of electric discharges or of simple sparks, that is to say, traces, ramified designs. may be determined upon the surface of these plates, which become visible if breath be projected upon them, and which, on this account, he had termed roric figures. On closely examining pieces of mica, he satisfied himself that a plate of this substance, when exposed to a puff of breath, or held over water in a state of evaporation, becomes covered with a deposit of minute drops, which do not form a continuous film; whilst this film is continuous and perfectly transparent, instead of being disturbed, if the surface of mica is new, and has not been already exposed to

the air.* We might suppose that the renewed surface is not covered with water; on the contrary, however, it is because it has a great affinity for water, that it condenses it in a continuous film; which is proved both by the great electric conductibility that it acquires, and by the inspection that may be made of it by means of the microscope, which at the same time reveals these minute insulated drops upon the parts, where the surface is not new. On the other hand, on exposing it to the action of drying substances, or to that of vacuum, the surface becomes insulating, in consequence of the disappearance of the thin film of water. The difference between the old and the new surface of mica, is due to there being formed upon the former a film of foreign matter from the deposit of various substances, principally organic, that occur suspended in the atmosphere, — a film, that has not had time to form upon the renewed surface. It is the presence of this slightly fatty film, that constrains the water to deposit itself under the form of drops, instead of forming a continuous deposit.

The action of the discharge of sparks would therefore consist in driving away the foreign film, wherever the electricity has passed; and the difference in the manner in which the breath arranges itself, where this film exists, and at the spots whence it has disappeared, would thus render the traces of the electricity visible. However, the surface of mica, like that of glass, may itself be modified to a tolerable depth by the effect of the discharges, as we have already seen, which explains the persistency of the figures, which sometimes remain for several years.

Returning to Karsten's electric figures, it should be noticed that there are two series of discharges, those which occur in one direction, when the model, that is placed upon the insulating plate, is charged; and those which occur, when the electricity of the model, and that of the lower plate, neutralise each other. Now, as these two effects succeed each other very rapidly, there results a removal of the foreign film

* The surface of a plate of mica is easily renewed, by detaching a thin plate from it with the blade of a penknife.

from the parts of the insulating plate corresponding to the points, that are nearest together, and consequently the most salient of the model. We may even render this effect sensible, by substituting for this lower metal plate, a very smooth surface of resin; and the image of the model is discovered by means of a fine powder that is deposited, where the electricity has left its traces. The image produced on the metal plate is in like manner due to the removal of a foreign film, analogous to that with which the mica is covered, a removal that occurs wherever the discharges have passed. This is proved by the influence of polish, which consists, less in purifying the metal than in clothing its surface with a perfectly uniform foreign substance. This is also proved by M. Fizeau's experiment, in which a platinum plate, after having been very well polished with cotton impregnated with a mixture of putty powder and alcohol, gave excellent images, and no longer gave any, after having been purified by incandescence and its successive immersion in acid water and in pure water, until it was able to inflame hydrogen gas. Moreover, Karsten, on inspecting with the microscope the images, that are produced by the breath upon a metallic surface, very plainly recognised that they arise from the deposit of a very thin and continuous film of water, which occurs at the points, from which the foreign deposits have been removed. He has also proved that the image that has been determined upon a brass plate is reproduced upon it by a deposit of copper, when the plate is plunged into a solution of sulphate of copper, as negative electrode; a proof that the traces of the image corresponded upon the brass surface with the points, from which the foreign film had been removed.

For the same reason it is that the plates of mica, upon which the reproduction of the image occurs best, are those whose surface is very old, and which have not been renewed for a long time, either by electricity or by mechanical action.

However, it seems impossible for us to explain, in every case, the formation of electric figures, only by the part attributed to this organic film, that exists on the surface of bodies, especially when these figures are visible immediately, as well

upon insulating plates as upon plates of metal, without the assistance of vapour. We are obliged to admit that a true molecular modification is brought about upon the surfaces; and the proof is, that the images are not merely superficial and transitory, but they penetrate sometimes to a tolerable depth, and are very durable. Now, it is very probable that in Karsten's experiments, the molecular polarisation, experienced by the insulating substance, that is placed between the two metal plates, must be accompanied by a change in the position of the particles, at the places where the electric action is the strongest, namely in the points, corresponding to the most salient parts of the object in relief. In like manner, when the discharges occur, the particles of the lower metal plate must, in the points, where they are nearest to the relief, also undergo a molecular change, the effect of which is a superficial alteration, very slight, it is true, but nevertheless sensible. It might also happen that, in certain cases, the prolonged passage of successive electric discharges, would be attended with certain electro-chemical effects, and in particular with an oxidation in the parts of the metal surfaces, that are the nearest to the salient points of the medal.

With regard to Moser's figures, they seem to me to have the same origin as Karsten's, as we have said above. The appearance and the properties of these two sorts of images are so very similar, that it would be difficult to attribute them to different causes. Moser's images cannot be formed upon a plate of metal through a plate of mica; is it necessary that the plate and the object, if not in contact, shall at least be at a very small distance apart, circumstances, that are altogether unfavourable to the hypothesis, that the figures are produced by an invisible radiation. That which proves that electricity seems to play a part in their production, is that, according to Karsten's observation, if a piece of silver is placed upon a brass plate, care being taken to place them in communication, by means of a band of copper placed all round on the exterior, an excellent image is obtained; whilst the image is very bad, when the precaution has not been

taken of attaching the band of copper. In the former case, we have a true pair, in which the air, more or less moist, interposed between the brass plate and the piece of silver, plays the part of a liquid conductor; whence it follows that the surface of the brass must be oxidised in all the points where it has not been in contact with the piece. In the latter case, the neutralisation of the electricities occurring by the points of contact of the plate and the piece, the effect must be more confused, than when it is brought about regularly, by the intervention of the copper plate, by which the two metal plates are connected.

The necessity of an interposed film of air, for the production of Moser's images, has been proved by Knorr, who has demonstrated that, in very pure water, deprived also of air, as *in vacuo*, the images are either not formed at all, or very difficultly. This fact is favourable to the explanation, that we have been giving; but it is not the less a difficult matter to explain the formation of Moser's images, when the two metal plates do not touch. However, it is not impossible that, at the necessarily small distance at which these plates are placed in reference to each other, the electricity, developed upon one of them, by the action of the moist air, being condensed by the influence of the other plate, may be capable of producing sufficient effects to determine the formation of the images. We shall see in the Part, that is devoted to the sources of electricity, some examples of the liberation of electricity, under similar conditions.

We shall not detain ourselves with the other explanations, that have been attempted to be given of Moser's images, especially those of Hunt and of Knorr, who attribute them to a caloric cause; and, according to Knorr, to a reciprocal transmission of heat between the plate and the object. This latter philosopher, indeed, on heating the plates, obtains images, which he terms thermographic, and which are evidently due to an oxidation; since they cannot be produced with plates of platinum and gold. The action of heat consists especially in manifesting pre-existent differences in the molecular state of a

metal surface, probably because these differences determine in it corresponding differences in the oxidation, that is suffered by this surface, through elevation of temperature. Thus heat causes the reappearance of the effaced image of a daguerréotype, and the vanished impression of a piece of money, the well-polished surface allowing no sign or any figure to be visible. In all these cases, the heat does not determine the formation of the image, but simply renders its manifestation sensible.

Without entering into further details upon this interesting subject, which has been the object of the researches of very many philosophers *, we sum up by stating our opinion that the formation of the image is in every case an electrical effect, due to the influence that the transmission of electricity exercises over the molecular state of bodies, either by dispersing the particles, when they oppose an obstacle to it, or by physically or mechanically modifying them, when they allow a passage to it. We rest, 1st, upon the fact, that the most certain and efficacious manner of obtaining the figures under all forms is to employ electric discharges; 2ndly, upon the circumstance that, in all cases, in which the figures are produced, without the direct intervention of electricity, the conditions most favourable to this production are at the same time those that are equally so to a liberation of electricity.

We shall not here speak of the other figures or images, that may be produced by means of electricity, such as Priestley's rings, and those of Nobili, seeing that the former are due to the heat, that is the attendant of the electric spark, and that the latter are the effect of an electro-chemical decomposition; the study of these will naturally, therefore, find its place in the two following Chapters, which are devoted to the calorific and chemical effects of electricity in motion.

* We regret, in particular, not to speak of M. Masson's researches, as well as those of M. Morren, which are, however, of a nature to confirm the ideas, that we have put forth, in respect to the cause of these phenomena.

Velocity of the Propagation of Electricity.

Immediately after the discovery of the Leyden jar, the prodigious rapidity with which the electric discharge is propagated, was proved, both by making it pass through a numerous file of men, who all held each other by the hand, as well as by transmitting it through a length of two miles, in the Thames,— a space which it traversed instantaneously. The most accurate experiment was that made by Watson, on the 5th of August, 1748. The arc, for connecting the two coatings of a Leyden jar, was formed by an iron wire 12,276 feet in length, sustained in the open air by insulating supports of dry wood, and so arranged that its two extremities and its middle were in the same chamber with the Leyden jar and the electrical machine. The wire was interrupted midway in its length, and this solution of continuity was occupied by the body of the observer, who held in his hands the two ends of wire, separated by this interruption. At the moment of the discharge, the observer saw the spark that escaped between one end of the wire, and the inner coating of the jar, at the same time that he felt the shock, produced by this discharge; and he was never able to perceive the smallest interval between the two sensations; from which he concluded that the rapidity of the propagation through the wire is not measurable.

A long time after these first essays, in 1834, Wheatstone took up the examination of this question, according to a very ingenious process, applicable also to a great number of other researches. This process is founded upon the effects of the reflection of a distant luminous point, by a plane circular mirror, traversed by a horizontal axis, situated in its plane and passing through its centre, around which it turns with very great rapidity (*fig.* 188.). E is the mirror, fixed to the horizontal axis G F, carried by the two brass supports I and H. The image of the luminous point, according to the law of reflection, describes an arc of a number of degrees double of that described by the mirror in the same time; that is, in the time employed by the mirror, to pass from the position

in which the image of the luminous point has been visible to the eye at rest of the observer, to that in which it ceases to

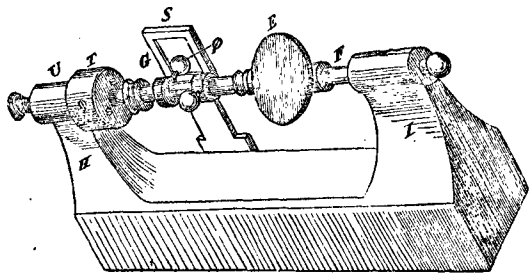


Fig. 188.

be so. If the duration of the light of the point is less than that of the time employed by the mirrors to pass from one of these positions to the other, the luminous arc will not have the length we have just assigned to it, in supposing this light permanent. If even this duration were nothing, and it could happen that the light should be completely instantaneous, the arc would be reduced to a point. Now, when the luminous point is an electric spark, arising from a discharge, produced in air between two conductors, the image, which is effectively nothing more than a point for a velocity of the mirror of 50 turns per second, becomes an arc for a greater velocity, a proof that the light of the spark has a certain duration. If we determined this velocity of the mirror, that is to say, the number of turns it makes in a second, we should be able, by measuring with a divided circle the number of degrees occupied by the image, to determine the time of the duration of the light, produced by the electric discharge, or, which comes to the same thing, the time of the duration of this discharge. Thus, Wheatstone, having found this arc to be 24° for a rotation of the mirror of 800 turns per second, concluded from this a duration of $\frac{24}{720 \times 800} = \frac{1}{24000}$ of a second. Indeed, during the time in which the mirror, while turning, traverses 360°, the image in it of the luminous point traverses 720°; now, as the mirror makes 800 turns

in the second, the image traverses 720' × 800, namely, 576,000° in a second; but as it has itself 24' of length, it must have endured for the time expressed by $\frac{24}{576000}$ or $\frac{1}{24000}$.

Thus, the first result obtained by Wheatstone is that the discharge, which produces the electric spark, is not completely instantaneous; but that it has a duration, excessively short, it is true, susceptible, however, of being estimated.

This point being established, the following is the process adopted by the English philosopher, for determining the duration of the propagation in a good conductor, such as a wire.

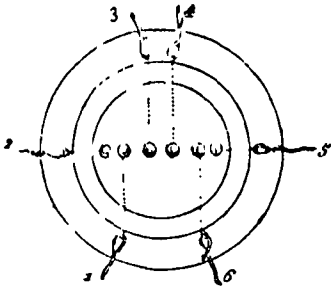


Fig. 189.

He constructed an apparatus, which he called a *spark-board* (*fig.* 189.), which consists of a wooden disc, upon which are placed, in the same horizontal line, six copper balls, combined in such a manner, that the same electric discharge may give rise to three sparks. Thus the ball, from which the wire No. 1. comes, communicates directly with the inner coating of the jar, whose discharge, passing to the next ball, goes from this ball by the wire 2, which is connected with the wire 3, to the third ball; thence it passes to the fourth ball, whose wire 4 leads it to the ball of wire 5, so that it may pass onward to the ball, whose wire 6 is in communication with the outer coating of the jar. The balls of each of the three systems are only $\frac{1}{10}$ in. apart from each other, and this constitutes the distance of the path for each of the three sparks; the circular spark-plate is $3\frac{1}{2}$ in. in diameter. Now the wires 2 and 3, as well as the wires 4 and 5, instead of being placed in immediate communication, are respectively united by a copper wire $\frac{1}{13}$ in. in diameter, and $\frac{1}{4}$ of a mile in length, which makes a total length of $\frac{1}{2}$ a mile between the ball 2 and the ball 5, a length interrupted in its middle by the balls Nos. 3. and 4. Thus the discharge, producing in the course three sparks, supposing it sets out from

the inner coating, has to traverse a copper wire $\frac{1}{4}$ of a mile in length, between the first and second spark, and a copper wire of $\frac{1}{4}$ of a mile also in length between the second and third. If the velocity of propagation in these long conductors is appreciable, the appearance of the three sparks should not be simultaneous; now, experiment shows that the spark at the middle is retarded, as compared with that of the two extremes, a proof, therefore, that the propagation of electricity is not instantaneous, and that it occurs from the extremities of the conductor by which the two coatings are connected, towards its middle.

The following is the manner in which Wheatstone arranges the experiment, in order to obtain this result, and to measure the velocity of the propagation.

The apparatus of *fig.* 188. is placed at the extremity of a mahogany plank (*fig.* 190.), upon which there is a wheel K,

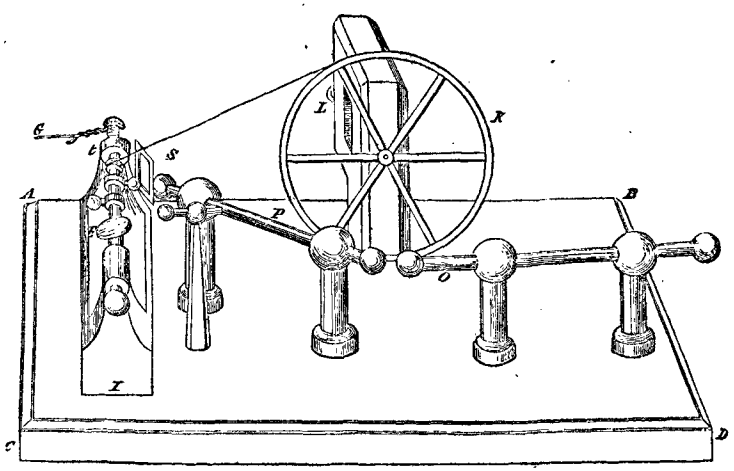


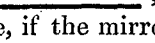
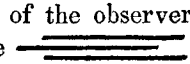
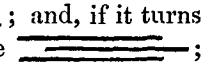
Fig. 190.

which communicates its motion to the axis, by means of a cord, passing in grooves, hollowed in the circumference of both pieces. In Wheatstone's apparatus, the system of wheels was so arranged that the axis carrying the mirror should have made 1800 revolutions for one of the wheel, if there had been no retardation, arising from the slipping of the

cord. A discharger O P is in communication by its extremity with the inner coating of a Leyden jar, which is constantly electrised by means of an electrical machine; the outer coating of the same jar communicates with the wire No. 1. of the spark-plate, and the wire No. 6. abuts against an enlargement of the brass support, upon which the axis of the mirror turns. The same axis carries an arm Q (*fig.* 188.), which turns with it, and which, at each revolution, is brought opposite to the knob of the discharger; this brings about the discharge, which, being transmitted through the circuit, passes between the two balls of the discharger, the distance of which is regulated for this purpose, then from the extremity of its stem P to the knob of the arm Q, and thence through the axis of the mirror to the spark-plate, where the eye perceives the three sparks. The plate itself is placed vertically at the distance of 9·84 ft. from the mirror, and in such a manner that the latter is upon the same level as the horizontal line upon which the three sparks are situated. The arm Q is so arranged that the discharge occurs, and that consequently the sparks appear, at the moment, when the mirror makes an angle of 45° with the horizon, which causes the eye of the observer, placed on the side of I, looking directly from above downward, to see the images of the three sparks, reflected upon a horizontal plane. A flat glass may be placed above the mirror, so as to prevent the eye approaching too near to the mirror. In order the better to regulate the instant of the discharges, which ought to occur at the moment when the mirror is inclined 45°, a plate of mica S is interposed, pierced with a very small horizontal opening, parallel to the axis of the discharger, which confines the possibility of the discharge within very narrow limits. Thus, whatever be the rapidity, with which the mirror moves, the sparks are generally in the field of view.

It is a matter of great importance, as may be supposed, to determine accurately the velocity of the rotation of the axis, that carries the mirror. Mr. Wheatstone arrived at this first, by calculating the pitch of sound, produced by the succession of blows received by a little band of paper or card,

attached to the arm Q, which, at each revolution of the axis, experiences a blow. When the machine had its maximum velocity, a sol sharp of the fourth octave was obtained, which corresponded to 800 revolutions of the mirror per second. More recently, Mr. Wheatstone has succeeded in furnishing the instrument with a counter for registering the number of rotations. It is true that the increase of resistance to motion, which arises from this addition, prevents the mirror executing more than 600 revolutions per second.

In operating by means of the apparatus, arranged as we have been pointing out, as soon as the velocity of the mirror exceeds a certain limit, the three sparks are seen to be elongated into three parallel lines, which are longer in proportion as the movement is more rapid. These lines are arcs of the circle, the centres of which are situated on the axis of the mirror; the greatest amplitude, they have been found to attain, was 24°, which, at 800 revolutions of the mirror per second, corresponds to a duration of the spark of $\frac{1}{24000}$ of a second, as we have seen. With regard to the relative position of the three images, when the velocity is yet feeble, their extreme points appear to be exactly in the same vertical, and present this appearance  ; but, as soon as the velocity becomes considerable, if the mirror is turning from left to right, in respect of the observer, placed at I, the lines assume this appearance  ; and, if it turns from right to left, they assume this appearance  ; which indicates equally in both cases that the middle spark appeared after the two extreme ones, and that it disappeared also after them. Indeed, in the former case, the mirror having passed the 45° on the side of the vertical, when the middle spark shows itself, it is clear that the commencement of its image must be found in arrear of the commencement of those of the other two sparks, which have appeared at the moment, when the mirror was at 45°; this must be the reverse in the case, when the mirror turns from right to left. Mr. Wheatstone has succeeded in estimating, approximately to half a degree, the amount, by which the middle image is in arrear or in advance of the other two. This arc of a half degree corresponds to a

duration of $\frac{1}{2 \times 360 \times 1600} = \frac{1}{1152000}$ of a second; the space traversed in this portion of a second being $\frac{1}{4}$ of a mile, or 1320 feet, which gives a velocity of 288,000 miles per second. This, then, would be the velocity of the propagation of electricity in a copper wire, a velocity superior to that of light in planetary space, which is only $\frac{2}{3}$ of the above.

Wheatstone's experiment proves, moreover, that in a wire which communicates, by its extremities, with the coatings of a Leyden jar, the electric derangement is propagated from the two ends of the wire with an equal velocity, and endures for a certain time, very short, it is true, but yet appreciable, in order to arrive at the middle of the circuit. We shall return hereafter, when engaged with the electric light, to certain experiments of Wheatstone's, which have reference to the duration of the spark.

Recent researches on the velocity of electricity, made with voltaic currents, transmitted through telegraph wires, have given very different results to those obtained by Wheatstone with ordinary electricity. Thus, Mr. Walker of Washington had found that this velocity, in an iron wire $\frac{1}{9}$ in. in diameter, was 18,760 miles per second, and Mr. Mitchell had found 28,526, both velocities being very much lower than the 288,000, that had been found by Wheatstone.

More recently, Mr. Gould took advantage of a colossal voltaic circuit of 1045 miles, established between the station of Seaton, at the north of the Capitol of Washington, and the town of Saint-Louis, with several intermediate stations, as Pittsburg, Cincinnati, in order to determine the velocity of the propagation of the current, according to a method altogether different; and he found 12,851 miles per second, and 15,830 in using only the experiments, made at a lower temperature than that of the congelation of water, the insulation not being sufficient at higher temperatures. Mr. Gould's method consisted in having a pencil fitted to a piece of soft iron, which, when resting on a white paper wound round a cylinder, to which a uniform rotatory motion is applied, by means of a clock movement, makes a regular mark upon it. The piece of

soft iron is attracted by the poles of an electro-magnet, surrounded by a wire, one end of which is led to the scape-wheel of a seconds pendulum. This wheel periodically interrupts the circuit which, by the action of the electro-magnet upon the armature, produces intermittences of attraction, which are interpreted by the equal and equidistant interruptions of the tracing upon the paper. A similar apparatus being arranged in each of the consecutive stations, they are all actuated by a single electric current, which traverses their common circuit. Mr. Gould first satisfied himself that the difference of the intervals between the marks at the different stations corresponded well with their distance from the place at which the signal was given, and that it was proportional to the time consumed by the current, in traversing double * the distance between the stations. By thus comparing the registers of each station, including that from which the current set out, he arrived at the result that we have indicated.

MM. Fizeau and Gonelle had obtained very different results, by operating in a still different manner. The principle of their method consisted in interrupting a current at very limited intervals of time, and simultaneously in two points of a long conductor, very distant from each other. These interruptions were brought about, by means of a wheel, carrying upon its circumference a number of equal divisions alternately in wood and metal, like the rheotomes, that we have already described †; these apparatus could be easily arranged in such a manner, that the circuit could be interrupted at two or at several places, and the interruptions should be perfectly simultaneous, wherever they occurred. A galvanometer, placed in the circuit, received by this arrangement only discontinuous currents; nevertheless, when the interruptions succeeded each other rapidly, the needle of the instrument was deviated in a stable manner, as if the current had been

* *Double*, on account of the necessity of the current to return to the point of departure.

† Vol. I. p. 301. (*fig.* 130.), and p. 302. (*fig.* 131.), p. 398. (*fig.* 153.)

continuous. Only the amplitude of the deviations varied with the number of interruptions, that occurred in a given time, and obtained a maximum for a certain number of interruptions, in the same time, that it acquired a minimum for another. If the propagation of the current in a long conductor is instantaneous, it is clear that the fact that the circuit suffers simultaneous interruptions at the two extremities of this conductor, should in no way change the deviation of the galvanometer, which remains the same as if there had been interruptions only in one point of the circuit. But, if the propagation requires a certain time, for its being brought about, it can no longer be the same, seeing that at the same moment when the interruption takes place at the point of departure of the current, it occurs also at the other extremity of the conductor, at which this same current has not yet arrived. When, therefore, it arrives there, it no longer finds the interrupter in the same position, and the deviation of the galvanometer there suffers a diminution. It follows from this, that the velocity of the propagation must give rise to periodical changes in the deviations, corresponding to greater and greater velocities of the rheotomes; and that consequently, from these changes, we might be able to deduce the velocity itself. MM. Fizeau and Gonelle did this, using for their experiment the telegraph wires from Paris to Rouen and from Paris to Amiens. The two wires of each of these lines might be connected, the former at Rouen, the latter at Amiens; they thus presented a length of 195 miles for the Amiens line, and 179 miles for that of Rouen. By operating according to the method, that we have been pointing out, by means of these long conductors, of which one was of iron and the other of copper, the two philosophers arrived at the conclusion that the velocity of the propagation of electricity is independent of the intensity of the current and of the section of the conductor, but not of its nature, and that it is 62,130 miles per second in an iron wire, and 111,834 miles in one of copper. Mr. Latimer Clark had already observed, by operating with piles, whose number varied from 31 to 500, and upon a length of wire of 768

miles, that the currents are propagated with the same velocity, whatever their intensity may be.

It was by means of Mr. Walker's astronomical observations in America that he satisfied himself, as we have seen, that the voltaic current requires an appreciable time for propagating itself in a long conductor. By employing the current for the determination of the difference of longitude between two stations, he proved that this propagation is not instantaneous; thus between Philadelphia and Cambridge, calculation showed that the current, setting out from one of these towns, at the moment of the passage of a star, did not arrive at the other at the same instant, and that it was necessary to take account of the time that had elapsed, which in this instance was $\frac{1}{2}\frac{1}{0}$ of a second, for the determination of the difference of longitude. The comparison of several observations made between the three stations of Washington, Philadelphia and Cambridge, led Mr. Walker to a velocity of 18,639 miles per second. Mr. Mitchell, of the Observatory of Cincinnati, as the result of numerous trials upon the telegraph line, extending from Cincinnati to Pittsburg, had found by the same method 28,331 miles per second. Finally, the astronomers of the observatories of Edinburgh and Greenwich obtained only 7600; and those of the observatories of Greenwich and Brussels only 2700, namely a hundred times less than Mr. Wheatstone. We should mention that, in this latter case, the copper wire for establishing the communication between Greenwich and Brussels, was, for a great part of the distance, submerged in the sea.

The following is a Table which, by summing up the determinations, made according to the different methods, of the velocity of the propagation of electricity, expresses clearly the great differences, that exist in this respect between the results obtained by the different observers.

Names of the Observers.	Nature of the Wire.	Velocity in Miles per Second.
Wheatstone - - - -	Copper.	288,000
Fizeau and Gonelle - - -	„	111,834
Idem - - - -	Iron.	62,130
Mitchell - - - -	„	28,331
Walker - - - -	„	18,639
Gould - - - -	„	15,830
Astronomers of Greenwich and Edinburgh - - - -	Copper.	7,600
Astronomers of Greenwich and Brussels.	„	2,700

It is to Faraday we are indebted for having found the causes of these enormous differences, and for having shown that the numerical results, contained in the above Table, do not depend simply on the velocity of the propagation of electricity; but depend also upon a phenomenon of an entirely different nature. In his first researches upon the propagation of electricity in bad conducting bodies, Faraday had already remarked, when speaking of Wheatstone's experiment, that the velocity of the discharge may greatly vary, according to the tension or intensity of the first impulsive force. He even added that the retardation of the mean spark, in relation to the extreme sparks, would probably become more sensible if the two extremities of the wire, by which the discharge was transmitted, were in direct communication with two large insulated metal surfaces; and especially if these two large surfaces were, one the inner and the other the outer coating of a Leyden jar. Now, the learned English philosopher has latterly confirmed the accuracy of his conjecture by means of direct experiments, made with telegraphic wires covered with gutta percha, intended for the establishment of submarine and subterranean lines. Having procured two hundred coils of these wires, each half a mile in length, he suspended them to a series of barges, ranged in a canal, so that each coil was plunged entirely in the water, with the exception of a short length of wire at each of the ends. He then connected end to end the extremities of the wires of each coil, deprived of their

insulating envelope, so as to constitute a single wire of 200 miles in length; and he connected one of the ends of this long wire with one of the poles of a battery, placing in the circuit a very sensitive galvanometer. The battery was composed of 360 pairs of zinc and copper, charged with acidulated water; it was perfectly insulated, and communicated with the ground only by its other pole. At the moment, when communication was cut off between the pile and the long wire, a very strong shock was felt, on touching either end of the long wire; this shock was of such duration, that it might be decomposed, by touching the wire for an instant only each time, into some forty successive shocks. If, instead of touching one of the ends of the wire, it was put into communication with one of the ends of the galvanometer, the other end of which was connected with the ground, the needle was powerfully deflected, and the effect was still sensible, when the experiment was not made till half an hour after the communication between the wire and the pile had been interrupted.

It is evident that this result is due to the formation of a Leyden jar of enormous size, by means of the long wire, the envelope by which it is insulated, and the liquid conductor, by which it is surrounded; which must consequently be charged by a considerable quantity of electricity, when its inner coating, which is the wire, is in communication with a source of electricity, even when this electric source is of feeble tension, as one of the poles of the pile.* In the experiment we have mentioned, the copper wire being $\frac{1}{6}$ in. in diameter, and the coating of gutta percha $\frac{1}{4}$ in. in thickness, it follows that the inner coating of the Leyden jar, formed by the long wire plunged in the water, presented a surface of 8300 sq. ft. in extent, and the outer coating 33,000. Moreover, the phenomenon is naturally more decided, in proportion as the pile has greater tension, and is consequently

* Volta, immediately after the discovery of the pile, had shown that a Leyden jar might be charged by putting its inner coating in communication with one of the poles of the pile, the other pole being put in communication with the ground.

composed of a greater number of pairs, the surface of the pairs, on the contrary, being a matter of indifference.

It is very curious to see the galvanometer, that is in the circuit, strongly deviated at the moment when one of the ends of the long wire is put into communication with one of the poles of the pile, even when the wire is insulated; this effect is evidently due to the passage of the electricity, by which the inner coating of this kind of jar is charged. In like manner, at the moment when communication with the pile is cut off, a strong deviation is obtained in the contrary direction, provided the end of the galvanometer, that is not in communication with the end of the long wire, is in communication with the ground. This latter deviation manifests the discharge, as the former indicated the charge.

The effects that we have been describing had already been observed by Siemens by means of the subterranean telegraphic wires, established in Prussia. He had noticed in these wires, provided they were well insulated, the establishment of the instantaneous currents of charge and discharge, that we have been pointing out; the former taking place at the moment when one of the extremities of the long wire was placed in communication with one of the poles of a pile; and the latter, at the moment when this communication ceased, and when a conductor, in communication with the ground, was substituted for the pile. In analysing this phenomenon, M. Siemens had well discerned the true cause; he had recognised in the copper wire the inner coating of a Leyden jar, of which the moist ground was the outer coating, and the gutta percha coating, the insulating layer.

To the facts that we have been stating, Faraday added another that is still more curious, and which is, however, the consequence of the same principle. He made use of four subterranean wires, each of about 375 miles in length, which are established between London and Manchester; at the Manchester station, he connected together the ends of the first and second wire, and those of the third and fourth. At the London station, he placed one of the ends of the galvanometer wire, in communication with the end of the first

wire; the other end of the galvanometer being fixed to the pole of a battery, that had its other pole in communication with the ground; by the wire of a second galvanometer, he connected the ends of the second and third wires; and, finally, he attached a third galvanometer, communicating also with the ground, at the end of the fourth wire. At the moment when this circuit was closed, the needle of the first galvanometer was immediately deflected, that of the second was not so until after a sensible interval, and that of the third a little later still, about two seconds after that of the first. The communication of the first galvanometer with the pile was interrupted; the needle of this galvanometer immediately returned to zero; that of the second did not begin to displace itself until a short time after; and that of the third, later still. On making and breaking this communication, at sufficiently near intervals, we are able, so to speak, to produce in the wire successive electrical waves, so that the three galvanometers are traversed at the same instant by three different waves. And if, after having suppressed the communication of the first galvanometer with the pile, this galvanometer is made to communicate with the earth, the electricity with which the wire is charged, discharges itself simultaneously by its two extremities; so that the first and third galvanometers are deflected at the same time in opposite directions.

When, instead of subterranean wires, Faraday made use of wires, freely suspended in the air, the effects were very little marked; all three galvanometers were deflected and returned to rest almost at the same instant. In this case there was no Leyden jar, for there was no outer coating, and consequently no possible lateral induction. Thus, this induction, as we have seen above, is able to retard by two seconds the propagation of the electric wave in subterranean wires 1,500 miles in length; a propagation, which is instantaneous in a wire of the same length, insulated in the air. However, even when the wire is not plunged in water, or placed in the moist ground, it may happen that the proximity of the ground, when it is very near, or the presence of neighbouring conductors, such as a conducting

wall, may determine a lateral induction, much less powerful, it is true, but still susceptible of retarding more or less the propagation of electricity. It is to this circumstance, which varies according to the arrangement of the telegraphic wires, that may in a great measure be attributed the considerable differences, that we have remarked in the results obtained by different observers, on the velocity of the propagation of electricity; differences so great that, in the above Table, the first number is the centuple of the last. It is true that the experiment, that had given this last result, was made with a wire immersed in water, for the greater part of its length; while that which had furnished the first, was made with wires stretched parallel and at a sufficient distance from each other and from the ground, and connected alternately end to end, so as to form but one continuous wire, bent several times upon itself. However, in this case, there was still a slight induction, brought about by the walls and the floor of the room, in which the wires were stretched; perhaps also of the wires upon each other *; which explains the small retardation, experienced by the middle spark in respect to the two extreme sparks.

It follows, therefore, from Faraday's labours, that the experiments, by which the velocity of the propagation of electricity had been supposed to have been measured, are by no means conclusive. They were, in fact, founded upon a false analogy which had been attempted to be made between electricity and the radiating agents, as light and heat. The propagation of electricity is of an entirely different nature; it evidently results from a modification, impressed upon the ponderable matter, interposed between the two electric principles; a modification, that may be compared with that, experienced by a series of ivory balls, which transmit the motion, that is received by the first, or like an elastic body, that propagates sound; which causes the velocity of the propagation necessarily

* The actual distance apart of these wires was, six inches; and they might consequently influence each other.

to vary with the bodies, upon which it is exercised, and with the circumstances under which they are placed, as was observed by MM. Fizeau and Gonelle. It seems to us that it must also vary, at least in the value that is given to it, with the nature of the effects, by which the electricity indicates its presence. It follows, of course, that we are here speaking only of the rapid propagation of electricity; for slow propagation is a phenomenon of quite another kind; and it is not with this that we are now engaged.

Mr. Wheatstone has added some new facts to those which had been observed by Faraday, taking advantage for this of a cable, 110 miles in length, containing six copper wires $\frac{1}{16}$ in. in diameter, each covered with an insulating coat of gutta percha of $\frac{1}{10}$ in. The whole was covered with twelve strong iron wires, wound spirally, which formed a metallic jacket of $\frac{1}{3}$ in. in thickness. The cable was coiled into a spiral in a dry pit in a yard, and one of its extremities extended into the interior of a room. The ends of the six wires might be united so as to cause the current to pass in the same direction through the six wires, added end to end, or else through some of them only.

The first experiments, made by Mr. Wheatstone, showed him that the iron jacket of the compound conductor gave rise to the same phenomena of induction, as Faraday had obtained by plunging the insulated wire into water. Also, the wire 660 miles in length was charged with positive or negative electricity, on placing one of its extremities in contact with the positive or negative pole of the pile, whilst its other extremity was insulated; but it was nevertheless necessary that the other pole of the pile should be in communication with the ground. However, if this pole was placed in contact with the extremity of a second wire, whose other extremity was insulated, the two wires were in like manner charged. The movement of the galvanometers, either during the charge, or during the discharge of the wires was such as Faraday has indicated. The following experiment

renders very evident the successive mode of the propagation of electricity.

The two extremities of the 660 miles of wire being placed in contact, each with one of the poles of the battery, when one of the extremities previously detached was again attached to the pole, the galvanometers placed at the extremities of the wire, and consequently at equal distances from the poles, were influenced immediately and simultaneously, whilst those which were in the middle of the wire were not set in motion until afterwards. When the circuit was interrupted in the middle of the wire, on establishing contact, the influence of the current was first felt on the central galvanometer, that is to say, on the most distant from the pile; then afterwards upon those which were towards the poles.

The following now is an experiment, which shows well that the long wire acts as a considerable conductor, in which the electricity is dispersed, similar in this respect to the terrestrial globe, except that, with the wire, the size of the induction being limited, the current ceases, as soon as the charge is complete. One of the poles of the pile is placed in communication with the ground, whilst the other is in contact with one of the extremities of the wire, whose other extremity is insulated; increasing lengths are given to this wire, and a sensitive galvanometer, placed between the pole and the wire, gives induction of a current, stronger in proportion as the length of the wire is greater, as is shown in the following Table, which contains the deviations of the needle, corresponding to the different lengths of the wire: —

0 miles	0°
110 „	6¼
220 „	12
330 „	18
440 „	23¼
550 „	28
660 „	31

On placing the galvanometer at different distances from the pile, the wire having always the same length, it was found that the deviation went on diminishing, setting out

from the point, where it is immediately in contact with the pole, to that in which it is at the very end of the 660 miles of wire, being in this latter case null. The intensity of the current appeared to depend solely upon the length of the wire that is added to that extremity of the galvanometer, which is not in communication with the pole, and to be entirely independent of the length of that which separates the other extremity of the galvanometer from the pole. This result proves that, whatever be the length of the insulated wire, connected with the pole of a pile, it is charged in its whole length with the same degree of tension; so that if another insulated wire is added to its free extremity, the latter presents the same phenomenon as if it had been placed in immediate contact with the pole of the pile. From this, therefore, we may conceive that when we place the extremity of a galvanometer, whose other extremity is attached to one of the poles of a pile, in communication with the terrestrial globe, the latter may be considered as an indefinite conductor, and then we obtain the maximum intensity, and an indefinite duration of the current.

The researches of Mr. Faraday, and of Mr. Wheatstone, show us, that the propagation of electricity is made, as it were, by a series of waves, analogous to those by which sound is propagated.* It is not, therefore, astonishing that the velocity of the propagation varies with the bodies through

* The experiments of Mr. Latimer Clark, which we have given above (p. 190.) while they show that the velocity of the propagation of the current is the same, whatever the tension of the pile may be, furnish a very strong proof in favour of the analogy that we admit between the mode of propagation of electricity, and that of sounds, which are propagated in the same medium with the same velocity, even when they are more or less sharp, or more or less intense. This had been remarked by M. Melloni, at whose request Mr. Latimer Clark had undertaken the important experiment, of which we have made knownthe results. The learned Italian philosopher had also observed, that the retardation in the velocity of the current, experienced in subterranean wires, by the effect of lateral induction, must be the same, and that consequently the absolute velocity must also be the same, whatever may be the tension of the pile; and this because the portion of electricity that is diverted upon the side of the coating of the wire, by the effect of the induction (which produces the retardation) being retained there by a force arising from this electricity itself, it must necessarily vary in proportion to its intensity, and consequently produce a retardation, that is always the same.

which it takes place, as has been observed by MM. Fizeau and Gonelle.*

We shall not terminate this subject, without remarking the still more intimate connection that the new experiments, of which we have been speaking, contribute in establishing between static and dynamic electricity. We have long known, thanks to the researches of Mr. Colladon, that a current may be produced, capable of acting upon the galvanometer, on drawing off by a point the static electricity accumulated upon an insulated conductor. We now see the converse, namely, that on introducing a current into an insulated conductor, it may be charged with static electricity. The dynamic state, like the static state, are therefore merely two forms, variable with the arrangement of the apparatus and of the experiments, under which one and the same agent is presented.

* More recent experiments, made by MM. Guillemin and Burnouf, on the velocity of the transmission of electricity in telegraph wires, have given for the velocity in an iron wire 111,847 miles per second, a velocity a little more considerable than that found also for iron by MM. Fizeau and Gonelle. MM. Guillemin and Burnouf operated between Foix and Thoulouse on a line formed by two parallel iron wires ·15 in. in diameter, and 51 miles in length, which made, on joining them end to end, a total length of 102 miles. Their process consisted in placing one of the ends of the wire in contact with one of the poles of a pile, whose other pole communicated with the ground, whilst the other end of the same wire was in contact with one of the extremities of a galvanometer whose other extremity communicated with the ground. Toothed wheels established and interrupted, a greater or less number of times per second, the contact of the two ends of the wire respectively with the pole of the pile and the galvanometer; the contacts and non-contacts were simultaneous at both these ends. If the propagation of the current was instantaneous, its transmission should always have taken place; but if it required a certain time for traversing 102 miles, we are able by turning the wheels with a continually increasing rapidity, to obtain a velocity such, that the current, that sets out from the pole at the moment in which the contact takes place, does not arrive at the galvanometer at the other end until the moment when this contact no longer takes place, the galvanometer is then no longer affected, and the interval of time that has passed between the instant of contact and that of non-contact is that, which the current has employed for traversing the wire 102 miles in length. MM. Guillemin and Burnouf employed four toothed wheels instead of two, two of these four being necessary for discharging the wire at its two ends, in the interval of the two successive contacts with the pole of the pile, and acting alternately with the two former, by causing the two extremities of the wire to communicate with the ground. We should further remark, that we never succeed in having an entirely null deviation in the galvanometer; but merely a minimum deviation, which is due to an effect of induction, arising from the proximity of the two wires, whose union forms the total circuit; but this circumstance changes nothing in the results, providing care is taken to observe the velocity of the toothed wheels, that corresponds to the minimum deviation.

In terminating this paragraph and this Chapter, we cannot refrain from remarking by anticipation, in order to justify the extent we have given to it, how much the general and at the same time the detailed study, that we have made of the propagation of electricity, will facilitate what we are about to advance of the phenomena, to which this propagation gives rise.*

* *List of the principal works relating to the subjects treated upon in this Chapter.*

De la Rive.—Distribution and laws of the propagation of dynamic electricity. *Mémoire de la Soc. de Phys. et d'Hist. Nat. de Genève*, t. iii. p. 109. *Annales de Ch. et de Phys.* t. xxviii. p. 190.—Influence of heat upon electric conductibility. *Bibl. univ.* t. vii. p. 388.

Kirchoff.—Laws of distribution in a metal plate. *Annales de Ch. et de Phys.* (new series), t. xl. pp. 115. and 327.; t. xli. p. 496.

Fechner.—Experimental laws of the intensity of currents, in a closed circuit. 1 vol. in 4to. Leipsic, 1831.

Pouillet.—Idem. *Comptes rendus de l'Académie des Sciences de Paris*, t. vi. (1837) p. 267. *Traité de Physique.*

Wheatstone.—Rheostat and electrical instruments. *Annales de Ch. et de Phys.* (new series) t. x. p. 257.—Velocity of electricity. *Philosophical Transactions of the Royal Society of London* (1836) part ii. p. 583.; and *Archives de l'Electricité*, t. ii. p. 35.

Jacobi.—Standard of resistance. *Comptes rendus de l'Académie des Sciences de Paris*, t. xxxiii. (1851) p. 280.

Matteucci.—Propagation of dynamic electricity in liquids. *Annales de Chim. et de Phys.* t. lxiii. p. 256.; and t. lxvi. p. 225.—Conductibility. *Annales de Ch. et de Phys.* (new series) t. xv. p. 498.—Propagation in bad conductors. *Annales de Ch. et de Phys.* (new series) t. xxvii. p. 133.; and t. xxviii. p. 385.

Marianini.—Propagation in liquids. *Annales de Ch. et de Phys.* t. xxxiii. p. 141.; and t. xlii. p. 131.

Ohm.—Laws of the propagation of currents. *Archives de l'Electricité*, t. i. p. 30.

Kohlrausch.—Mode of propagation of the current. *Arch. des Sciences phys.* t. xxii. p. 105.

E. Becquerel.—Conductibility of solids and liquids. *Annales de Ch. et de Phys.* (new series) t. xvii. p. 262.; and t. xx. p. 53.—Conductibility of gases. *Idem.* t. xxxix. p. 355.

Lenz.—Conductibility of certain bodies. *Bibl. Univ.* (1838) t. xvii. p. 38. *Idem.*—Conductibility at different temperatures. *Annales de Ch. et de Phys.* t. xxxix. p. 355.

Wartmann.—Conductibility of mineral substances. *Mémoire de la Soc. de Phys. et d'Hist. Nat. de Genève*, t. xxiii. (1st part). *Arch. des Sciences phys.* t. xxii. p. 84.

Hankel.—Influence of heat on the conductibility of liquids. *Arch. des Sciences phys.* t. vi. p. 66.

Riess.—Electric conductibility of certain solid bodies, and of non-conducting bodies. *Arch. de l'Electricité*, t. ii. pp. 91. and 177.—Explosive distance. *Idem.* t. i. pp. 206. and 425.—Electric images. *Arch. des Sciences phys.* t. i. p. 425.

Vorsellmann de Heer.—Influence of heat on electrodes. *Arch. de l'Electricité*, t. i. p. 589.

Beetz.—Same subject. *Arch. des Sc. phys.* t. xiii. p. 282.

Karsten.—Conductibility of sulphurets. *Arch. des Sc. phys.* t. v. p. 350.—Electric figures. *Arch. de l'Electricité*, t. iii. p. 310.; and t. iv. p. 457.

Rousseau.—Apparatus for imperfect conductibility. *Annales de Ch. et de Phys.* t. xxv. p. 393.

Wiedemann.—Conductibility of crystals. *Arch. des Sc. phys.* t. xxii. p. 44.

De Sénarmont.—Same subject. *Annales de Ch. et de Phys.* (new series) t. xxviii. p 257.

Knoblauch.—Direction of crystals between two electric poles. *Annales des Sc. phys.* t. xix. p. 214.

Ermann.—Unipolar conductors. *Ann. de Ch.* t. lxi. p. 113.; and *Annales de Ch. et de Phys.* t. xxv. p. 298.

Peltier.—Vaporization favoured by electricity. *Annales de Ch. et de Phys.* t. lxxv. p. 330.—Molecular modifications of conductors. *Comptes rendus de l'Académie des Sciences*, t. xx. (1845) p. 62.; and *Arch. des Sc. phys* t. v. p. 182.

Andrews.—Conductibility of Flames. *Bibl. Univ.* t. vi. (1836) p. 158.

Belli.—Difference between the velocity of the dispersion of the two electricities. *Bibl. Univ.* t. xxiii. (1838) p. 196.

Morgan.—Conductibility of vacuum and propagation in imperfect conductors. *Bibl. Brit.* t. ii. p. 119.; and t. xii. p. 3.

Harris.—Electric influence of rarefied air. *Bibl. Univ.* t. xvii. (1838) p. 195.; and *Philosophical Transactions* (1834) (part ii.) p. 203.

Davy.—Conductibility of vacuum. *Annales de Ch. et de Phys.*, t. xx. p. 168.

Fusinieri.—Transport of solid substances by discharges. *Archives de l'Electricité*, t. iii. p. 597.; and t. v. p. 516.

Moser.—Images. *Comptes rendus de l'Acad. des Sciences*, t. xv. (1842) pp. 119. 448. 855. and 1201.

Knorr.—Electric images. *Arch. de l'Electricité*, t. v. p. 115.

Hunt.—Same subject. *Idem.* t. v. p. 5.

Morren.—Same subject. *Comptes rendus de l'Acad. des Sc.* t. xvi. pp. 1078. and 1303.; and t. xvii. p. 87.

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Walker and Gould.—Velocity of electricity. *Ann. des Sc. Phys.* t. xix. p. 303.

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Faraday.—Electric conductibility, discharges, &c. *Collection of Memoirs extracted from the Phil. Trans.* from 1832 to 1838. in 1 vol. 8vo.—Induction exercised by propagation in long wires. *Arch. des Sc. phys.* t. xxv. p. 209.

Becquerel, sen. Conductibility. *Ann. de Ch. et de Phys.* t. xxxii. p. 420. *Traité de l'Electricité.*

CHAP. II.

CALORIFIC AND LUMINOUS EFFECTS OF DYNAMIC ELECTRICITY.

Forms and Conditions under which Heat and Light are produced by Dynamic Electricity.

We have already made mention of the property, possessed by electricity in motion, of giving rise, during its transmission, to heat and light. We have even described calorific voltameters, founded upon the heat, that is developed by the electric current, while traversing a fine wire.* We have already explained some of the phenomena of heat and light, that are produced by electric discharges, under the form of sparks or of incandescence, and of the fusion of metals.† We are now called upon to study more closely this class of facts, to examine their details, and to search out their laws.

The heat and light that accompany the reunion of the two electricities, or the condition that we have designated by the name of dynamic electricity, present themselves under very various forms. The most simple and most direct is the elevation of temperature that results in a conductor, from the passage of dynamic electricity, either continuous as a current, or instantaneous as a discharge. This elevation of temperature is the more considerable for the same conductor in proportion as this conductor has less dimensions, and consequently as it presents greater resistance to the transmission of electricity, and a less volume to the action of the liberated heat. It also varies with the nature of the conductors; but it occurs in all, as well in liquids as in solids, only in different degrees, according to their nature and their dimensions.

* Vol. I. p. 32. and following pages.
† Vol. I. p. 119. and following pages.

A second form, under which electric heat and light are manifested, is that which has been designated under the name of *electric spark* and *voltaic arc*. It differs from the former at the very outset, inasmuch as it always of necessity gives rise at once to light and heat; whilst the former produces obscure heat, and does not develope light until the heat becomes sufficiently intense to render the conductor incandescent. The latter form differs further from the former, inasmuch as the luminous and calorific phenomena are manifested by the passage of dynamic electricity, not through a continuous conductor, but between two conductors, charged with the contrary electricities, placed at a greater or less distance from each other, and separated by an insulating medium or a bad conductor, such as vacuum, an elastic fluid, or a liquid. The spark differs from the voltaic arc, with which in other respects it has many relations, in that it is the result of the instantaneous reunion of the two electricities; whilst the arc is produced by their continuous reunion; so that the arc may be regarded as composed of a series of sparks, succeeding each other very rapidly. The spark is generally produced by the discharges of electrical machines and Leyden jars, in the phenomenon, that we have called explosion; whilst the arc is manifested between two conductors, communicating each with one of the poles of a voltaic pile. However, the real identity that exists, notwithstanding the difference in appearance, between the spark and the arc, may be easily proved by employing, for their production, inductive currents, which are equally suitable for the manifestation of them both. A character common equally to the spark and the arc, is the transport of ponderable matters, which is always the companion of their manifestation.

Under whichever of the two forms the liberation of the light and heat produced by electricity is manifested, there exists, for one as well as for the other, one condition necessary to their manifestation: it is that dynamic electricity, in its transmission, meets with a resistance, and that it is in the points of a given circuit, where this resistance is the

greatest, that the heat and light are most intense. This first condition leads to a second: it is that the electrical apparatus may liberate electricities, endowed with a tension sufficient to overcome the resistance of the medium, through which their reunion is to be brought about.

In the examination that we are about to make of the phenomena, which we have been merely pointing out, we shall then commence with those that are manifested under the former form: namely, in the case in which the propagation of electricity occurs through a continuous conductor; we shall then pass on to those, that occur when the conductor is interrupted (electric spark and voltaic arc); we shall then terminate this Chapter, by a more special study of the electric light and its properties.

Calorific Effects, produced by the Passage of Dynamic Electricity through good Conductors.

It was not until after science had been put in possession of the Leyden jar, that the effect could be studied of the heat produced by electric discharges through good conductors. Franklin, by these discharges, succeeded in melting thin leaves of metal; Beccaria and especially Priestley, succeeded in the same manner in making wires incandescent, and even in melting them. Priestley had even made a very important observation, the accuracy of which was confirmed by all subsequent experiments; namely, that if the discharge of a powerful battery is passed through two successive wires, connected with each other end to end, of the same length and the same diameter, but of a different nature, only one of them is melted and dispersed, and this is always the one, that is the worst conductor of the two. Thus, of two wires, the one of iron and the other of copper, it is the iron, that is totally dispersed by the explosion, whilst the copper remains intact; of two wires, the one of copper, the other of silver, it is the copper, that is dispersed; and it is the silver, when the second wire is of gold, instead of copper.

Cuthberson, when operating in the air upon wires of

different metals $10\frac{1}{2}$ in. in length, and with a battery, whose inner coatings presented a surface of about 32 square feet, had obtained the following results: —

Name of the Metals.	Diameter of the Wires.*	Charge in Grains of the Electrometer.	Colours of the Metal Dust collected.
Lead wire -	$\frac{1}{10}$	20	Rather deep grey.
Tin „ -	$\frac{1}{10}$	30	Almost white.
Zinc „ -	$\frac{1}{10}$	45	„ „
Iron „ -	$\frac{1}{150}$	35	Reddish brown.
Copper „ -	$\frac{1}{150}$	35	Brown, tending to purple.
Platinum „ -	$\frac{1}{150}$	35	Black.
Silver „ -	$\frac{1}{150}$	48	„
Gold „ -	$\frac{1}{150}$	40	Brownish purple.

* The diameters are estimated in fractions of English inches.

By measuring, on the one hand, the charge of the battery, by means of an electrometer*, and, on the other hand, the calorific action produced by the discharge, taking as a unit of measure the length of iron wire of a given diameter melted, Cuthberson found that the calorific action was almost proportional to the square of the charge of the battery for certain lengths of wires; this law, which was merely glanced at by Cuthberson, who had only very imperfect means of observation, was rigorously established by Riess, as we shall see, presently, not for fusion, but even for the heating of wires.

With the great machine at the Teyler museum at Harlaem, Van Marum succeeded in melting an iron wire 52 ft. in length; and, by operating with wires of a different nature, but of the same diameters, he had found that the length he was able to melt with the same charge was greatest for lead, then for tin, iron, gold, &c. When the experiments take place in the air, the wires are not only heated and melted, but are also burned, if they are of an oxidisable metal. Priestley had already made the remark, although he had not at that time

* The weight-electrometer, employed by Cuthberson, is similar to the discharging electrometer, by the same philosopher (Vol. I. p. 118.), in which a small travelling weight may be placed at different distances from the axis of the apparatus, along one of the stems, which is divided so as to determine the discharge, only when a certain intensity of electricity is attained.

just notions of combustion; he had in particular observed that when iron wire is melted by the electric explosion, brilliant sparks are dispersed around the room in all sorts of directions, which is a sign of combustion. With steel wires, when the charge of the battery is not sufficient to melt them, their surface is seen to be covered with various colours, corresponding with the degrees of oxidation, they have undergone. Platinum and gold do not oxidise; but are simply melted and volatilised. In nitrogen, or in hydrogen, the other metals, by the effect of a discharge that disperses them, are simply reduced into a fine powder, not oxidised.

All the experiments, that we have been quoting, are made by means of the *dischargers* described Vol. I. p. 118.; and in globes, furnished with copper rods, which served to transmit the discharge to the wires, when the experiments were made in other media, than in ordinary air.

Very quickly after the discovery of the voltaic pile, it was observed that the passage of the electric current through wires was able, as well as the transmission of discharges, to heat them, to render them incandescent and to melt them; and that very intense phenomena of deflagration were obtained, in the same manner, with very thin sheets of metal, such as gold leaf. Cuthberson pointed out several important differences, between the effect of the current and that of discharges. Thus, besides the duration of ignition, that occurs in the former case and not in the latter, there is a further difference between the two modes, namely, that with charges there is produced an explosion, that disperses the wires and reduces them into powder, whilst nothing similar occurs with the current.

Fourcroy, Vauquelin, and Thénard were the first to remark that voltaic piles with large surfaces, although they have no greater tension for a given number of pairs, than have those with small surfaces, developed much more heat than the latter, in wires placed between their poles. Davy, on his part, found that, with a pile having large plates, water could immedi ately be raised to a state of ebullition by plunging into it an iron wire, two feet long, and $\frac{1}{100}$ in. in diameter, placed between the poles of this pile. The wire itself was able

to become red-white for a length of three or four inches. He had previously been the first to succeed in making red-hot and burning steel wires, thin leaves of tin, zinc, copper, silver, and gold. Each of these metals in burning gives forth a flame of a different colour, accompanied by a species of crepitation, and a remarkable kind of hissing. Zinc gives a blue flame; tin, a purple; lead, a yellow with a violet border; copper, a green accompanied with vivid sparks; silver, white in the centre, and green at the edges; gold, a brilliant yellow. All these metals oxidise in this deflagration; gold, in particular, passes into the state of brown oxide. Platinum alone, reduced into leaves as thin as possible, attains to white-red, melts, scintillates at its edges, but does not pass into the state of oxide.

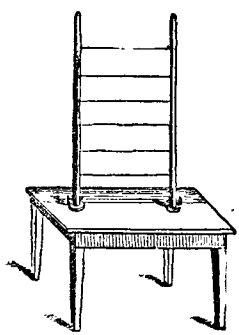

Fig. 191.

In order to make these experiments conveniently, it is necessary to have a small ladder, composed of two small vertical metal rods, fixed on a wooden base, and connected by thick brass wires, situated parallel and one above the other, at a distance of three or four inches (*fig.* 191.). Leaves of metal are suspended to ladders of this kind, so that the leaves of the same nature are suspended to the same wire; then, after having put the metal ladder in communication with one of the poles of the pile, the other is connected with a brass ball, or what is still better, with one of platinum, fixed at the end of a handle of wood or glass. The ball is then made to touch successively each of the thin leaves, and its deflagration and combustion is brought about by thus placing it in the voltaic circuit. In this manner, the phenomena of each metal leaf may be very well studied separately.

Children subsequently observed, on a large scale, and in a detailed manner, the calorific effects of dynamic electricity in good conductors. This philosopher made use of a battery, of 25 pairs of copper and zinc, each plate of which presented a surface of 62 square feet, and charged with acidu-

lated water. He commenced by interposing between the poles of this pile wires associated in pairs, so as to form a single conductor, composed of two lengths of wire of different natures, but of the same length and the same diameter; the worst conductor became heated, and even red, whilst the other remained cold; thus, on forming a metal chain of three wires of platinum, and three of silver alternately, all the platinum wires were seen to become incandescent, whilst those of silver were not so. This result is similar to that, which Priestley had obtained, when employing discharges in place of currents. Another experiment of Children's, which was suggested to him by Wollaston, consists in placing parallel to each other, in the circuit, two platinum wires of the same length; but one of them being $\frac{1}{25}$ in. in diameter, and the other only $\frac{1}{500}$ in.; the thickest of the two wires is seen to become red, whilst when the two wires are united, one following the other, it is the reverse, namely, the finer wire that becomes red. In the latter case, as they form part of the same circuit, it is not astonishing that the finer, which presents the greater resistance to the current, becomes the more heated; with regard to the former case, the larger, transmitting the greater proportion of electricity, and having a cooling surface in proportion to its volume, less than that of the finer wire, is the one that should acquire the more elevated temperature. Children, by means of his powerful apparatus, had succeeded in raising to incandescence and even to fusion very large and tolerably long platinum wires; one of them was $\frac{1}{5}$in. in diameter, and $2\frac{3}{4}$ feet in length; but all these effects have since been obtained on a very much larger scale by Grove's and Bunsen's battery.

The most convenient apparatus for producing the different phenomena of the incandescence of wires, that we have been describing, consists (*fig.* 192.), of two brass rods, fixed upon a small table, and each placed in communication, by a binding screw, one with the positive, the other with the negative pole of the pile. One of the rods carries binding screws, in which are affixed, by one of their ends, the various

wires that are proposed to be placed in this circuit; the other end of each of these wires is wound round a metal peg, which is itself fixed in a hole pierced in the second rod at the same height as the corresponding binding screw of the first rod, so that the wire, when stretched, should be perfectly horizontal. Now, in order to prevent the wires being all at the same time in the circuit, below each of the holes of the second column, a second similar hole is found, but coated interiorily with an insulating layer of wax, glass, or ivory. Into these holes the plugs are inserted, to which are attached the wires, that are not required to be placed in the circuit, leaving that, or those, that are required to be heated by the passage of the current, in the metal holes. In this manner, we are able to see successively the effect of the transmission of the same current in all the various wires, some homogeneous, others composed of pieces, alternately of one kind and of another, some larger, others finer; or to study this same effect simultaneously upon two wires placed parallel in the circuit; for example, a fine and a large platinum wire, two wires of the same diameter and length, one of platinum, and the other of silver.

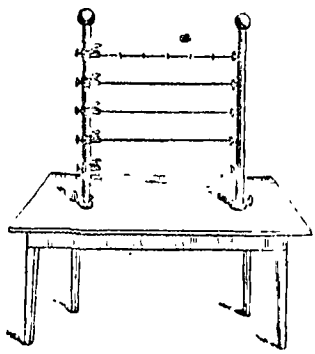

Fig. 192.

Whilst Children was observing on so large a scale the phenomena of voltaic ignition, Wollaston succeeded in heating to redness a very fine platinum wire $\frac{1}{2300}$ in. in diameter*, by means of a single small pair of zinc and copper of 1 sq. in. of surface.

* It is known that Wollaston procured these very fine wires, by placing a fine platinum wire in the axis of a cylinder of silver, and drawing the cylinder through a draw plate into as fine a wire as possible. One end of it is then taken and bent into the form of a U; the wire, with the exception of its two extremities, is then plunged for a few minutes into nitric acid; the silver dissolves, and there only remains the platinum of extreme fineness. The ends of this wire, which have retained their silver envelope, serve for rendering it sensible to the eye and the touch.

Metals and solid conducting bodies are not the only bodies that are heated by the effect of the passage of the electric current. Liquids also experience a considerable elevation of temperature; Davy had already proved this, in his experiments on the decomposition of water and of saline solutions, by dynamic electricity. Having placed in the circuit of a battery of a hundred pairs having small surfaces, two cones of gold, filled with distilled water and connected by a skein of asbestos, he placed a thermometer in each of the cones; he then added to the water of the positive cone a drop of solution of sulphate of potass; decomposition commenced, and was followed by an elevation of temperature, which became sufficient in two or three minutes to cause the water to enter into a state of ebullition. With a solution of nitrate of ammonia, the liberated heat rose so high, that it entirely evaporated the water in three or four minutes. Oersted subsequently observed, that in a column of water, traversed by the current, the elevation of temperature is more considerable at the positive pole (36°.9) than at the negative (32°.4), but that it is greatest (41°.4 F.) in the middle. I arrived at the same result as Oersted; but I, at the same time, had observed that the development of heat in the interior of a liquid mass, placed between the two poles of a pile, may be considerably augmented by dividing it into several compartments, by porous diaphragms made of bladder or gold-beater's skin. It is found that the temperature is higher in the middle compartments than in those of the extremities, and that in each compartment it is about 4° higher in the portion of the liquid in contact with the diaphragm of bladder than in the rest. If the same current is made to pass successively through a continuous liquid in a glass tube of a certain diameter, and a certain length, and through a skein of cotton of the same length and diameter as the tube, the temperature of the liquid contained in the tube, is seen to remain stationary, whilst that in the skein of cotton rises considerably, which is due to the cells of cotton, wherein the liquid is lodged, forming so many small compartments, separated from each other by diaphragms, which

the electricity is obliged to traverse. For the same reason stalk of a fleshy plant, which is a liquid conductor separated into a multitude of small cells by non-metallic diaphragms, becomes heated until the water it contains enters into a state of ebullition when, by means of two platinum points, it is placed in the circuit of a rather strong pile. Liquids are at all times placed in the voltaic circuit by means of wires or small plates of platinum, in order not to complicate the results by the chemical action exerted upon the surfaces of the electrodes, by the solutions, in which they are immersed.

Different liquids, placed in the route of the same current, present the same phenomena as metal conductors: namely, those which conduct least are heated most. By arranging in the same voltaic circuit, one after the other, several similar capsules, each filled with an equal quantity of water, or of different saline and acid solutions, connected two and two, by arcs of platinum, it is seen that the one in which pure water is contained, becomes heated 18° or 20° above the temperature of the surrounding air, whilst the others are scarcely heated. If the capsule filled with water is removed, the cell, among those that remain, which contains the worst conducting liquid, is always the one that becomes most heated.

All these experiments appear to point out in a decided manner that in liquids as in solids, the development of heat, produced by the passage of the electric current, arises from the resistance experienced by this current; since, wherever this resistance is greatest, there also is the elevation of temperature more considerable. This general law finds its further confirmation in several facts of another nature, that I have had the opportunity of observing, and to the most important of which I shall confine myself to relating.

The heat developed in equal quantities of similar conducting liquids, traversed successively by the same current, is more considerable in proportion as the electrodes present, both by their dimensions and their nature, greater resistance to the current, their distances remaining the same. By employing, instead of continuous currents, currents rendered discontinuous by means of a rheotome or a commutator placed

in the circuit*, a less elevated temperature is obtained in the liquid into which the discontinuous currents are guided alternately in contrary directions, than in that in which they are constantly guided in the same direction; but, as we shall see, in the Chapter upon electro-chemical decompositions, the transmission of electricity experiences much less resistance in the former case than in the latter. In order to make this experiment, we place consecutively two perfectly similar systems of liquid conductors, which are united and placed in the circuit by small plates of platinum; then, in the same circuit, we also place a fine platinum wire plunged into a given quantity of water, in which is placed the bulb of a sensitive thermometer. The same quantity of electricity † is made to pass in this succession of conductors, for the same time; and it is found that the sum of the quantities of heat, developed in the two liquid systems and in the platinum wire, is sensibly the same, whether the current be continuous or be discontinuous, and guided constantly in the same direction in the two systems; or finally, if it be discontinuous and guided in one of the systems, always in the same direction, and in the other alternately in contrary directions. Only in this case, the first system is heated more than the second, as we have said, and there is also more heat developed in the platinum wire.

It is very curious to see the liquid system, in which, the current always travelling in the same direction, there is a liberation of gas, become more heated than that wherein, on account of the alternately contrary direction of the current, there is no gas.‡ This result would appear to

* For the description of these apparatus, see Vol. I. p. 300. *fig.* 130.; and p. 398–9. *fig.* 153.

† That the same quantity of electricity has passed in each case, is made certain by placing in the circuit, but so that the discontinuous current always traverses it in the same direction, a chemical voltameter (Vol. I. p. 33.), and by stopping the experiment when the same volume of gas has been liberated.

‡ The absence of the production of gas is only apparent. It is due to the oxygen and hydrogen, which arise from the decomposition of the water, succeeding each other very rapidly on the surface of the same electrodes, on account of the alternately contrary directions of the currents; and there is a recomposition of the water, at the same time as a decomposition.

indicate that the formation of the gases does not diminish the quantity of heat liberated in a liquid by the current, which would depend only upon the resistance, that is experienced by the electricity. However, we have seen that in water, decomposed by the electro-chemical process, the elevation of temperature is less at the two poles, at which the two gases, oxygen and hydrogen are liberated, than it is between them; and that at the negative pole, where the liberation of gas (hydrogen) is greatest, it is most feeble. These differences would seem to demonstrate well that the formation of the gases is not without some influence; the more so as, when the column of water is traversed by discontinuous currents, guided alternately in contrary directions, a case in which this formation does not occur, all these differences disappear and the distribution of temperature in the liquid becomes perfectly uniform. We shall return to this important point, when we shall have studied the chemical effects of dynamic electricity.

After this rapid review of the principal results, obtained by the philosophers who have turned their attention to the calorific effects, brought about by dynamic electricity in its passage through good conductors, it remains for us to discuss the more precise laws which vigorous researches have enabled us to establish.

Laws which regulate the Calorific Effects of Discharges in good Conductors.

In order to study more closely the calorific effects of discharges, Harris and Riess both employed the air-thermometer, the bulb of which is traversed by a wire, which, in transmitting the discharge, is heated it to a quantity that is measured by the movement of the thermometric index. This apparatus, which we have described in the first part of the work *, in order to be able to furnish exact and comparable results, requires much care in its construc-

* Vol. I. p. 33. *fig.* 20.

tion; and it is probably to the imperfection of the one employed by Harris, that we must attribute the inaccuracy of some of the conclusions, that he deduced from his experiments. Harris, indeed, had thought he was able to establish that the calorific effects of an electric discharge, brought about through wires, depended only upon the quantity of electricity, and that consequently it is the same whatever be the tension of the electricity in the battery, provided the total quantity remains the same; a law which, as Riess has demonstrated, is not accurate. On the other hand, Harris succeeded in measuring very accurately the relation that exists between the quantity of heat, liberated by a wire and its electric resistance, by the effect of the transmission of the same quantity of electricity. The following is the Table that he gave of these relations: —

Metals.	Heating.	Resistance.
Silver	6	1
Copper	6	1
Gold	9	1½
Zinc	18	3
Platinum	30	5
Iron	30	5
Tin	36	6
Lead	72	12

It follows, as is manifest from the Table, that the heating is exactly proportional to the resistance, or, which comes to the same thing, is the reverse of the electric conductibility.

Riess, by the very special care, introduced into the construction of his electric thermometer, and by the very large number, as well as the scrupulous accuracy of his experiments, succeeded in establishing with remarkable precision the laws of the phenomena with which we are engaged. In announcing these laws, we shall endeavour to describe the processes that were followed by this skilful philosopher in order to arrive at them; at the same time regretting that the limits which are imposed upon us do not permit of our entering into so many details as we should have desired.

The electric thermometer is composed of a glass tube $17\frac{5}{4}$ in. in length, bent at right angles, at its two ends, one of which is terminated by a glass globe, $3\frac{5}{4}$ in. in diameter, the other by a cylindrical vessel $2\frac{5}{4}$ in. in height, by $\frac{5}{7}$ in. in diameter (*fig.* 193.). The tube furnished with a scale divided

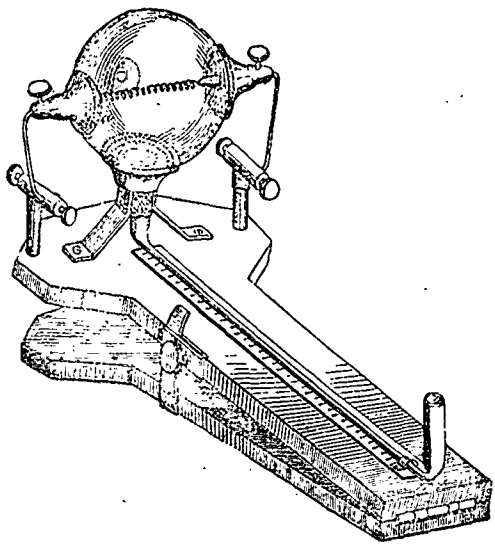

Fig. 193.

arbitrarily, is fixed on a wooden plank, attached by hinges to a horizontal base, so as to have facilities for being inclined at pleasure, in respect to the horizon, and for being adjusted in the position that is given to it, by means of a divided metal arc, and a binding screw. Coloured sulphuric acid, diluted with alcohol, is poured into the cylindrical vessel. The globe of the thermometer is perforated in three places, two of which are diametrically opposed to each other. Metal sockets cemented in these two openings, are closed hermetically by covers that are screwed upon them. The third opening is furnished with a piece of perforated metal, which is closed by means of a metal plug; it allows of the introduction into the tube of a liquid column of the given length. Into the two sockets there enter with friction two cylinders, about $2\frac{1}{4}$ in.

in length, by 2 in. in diameter, furnished at their outer end with a screw. At their inner end there is a cone, which is fixed to it by means of a screw; the base of each of the two cones is cut open, and into these clefts is introduced by its two ends the platinum wire, whose elevation of temperature we desire to determine. A rod of metal, that is easily passed through the globe is employed for introducing the platinum wire which it draws along; after the rod has been removed, the wire is strained by means of the screws. The covers of the sockets and the platinum wire are placed in the circuit of the battery by means of thick brass wires; the platinum wire on being heated by the discharge, expands the air in the globe and drives the liquid from the tube into the reservoir. The instrument is more sensitive, for given conditions, in proportion as the inclination of the tube towards the horizon is greater. In estimating the heating of the wire, the cooling of the air caused by the sides of the globe during the time, which is generally very short, of the falling of the liquid, is neglected; the surface, however, of the globe is surrounded by a very thin envelope of gutta-percha, covered with tinned plate, so as to prevent the variations of temperature that might arise from external causes. Now, by means of a formula founded upon the laws of heat, the increase of temperature that has been experienced by the wire is deduced from the space traversed by the liquid, estimated in linear divisions (lines or millimetres).* After having finished one experiment, the globe is opened, and the wire is allowed to cool; the metal plug is then gently replaced. If the cooling has been complete, the liquid, after having descended a certain quantity in the tube, stops; if not, it begins to rise again. We must take care not to select initial temperatures, too much differing from each other, in the experiments that are to be compared; for the heating of a platinum wire depends, in a certain measure, on its primitive temperature, and of which no account can be taken; hence the great importance of this temperature being at all times very nearly the same. In Riess's experiments it was about 60°.

* For the establishment of this formula, and its application to certain cases, see note C. at the end.

In order to establish the relation that exists between the force of a discharge and its calorific effects, we must in the outset have a means of measuring the quantity of electricity, with which a battery is charged. For this purpose we employ the electrometric jar (*fig.* 194.), which is a Leyden jar, whose metal rod, that communicates with the inner coating, is furnished with two balls, one, the lower of the two, intended to be put into communication with the outer coating of the battery, which is carefully insulated, the other, the upper one, placed opposite to a perfectly similar ball, situated at the same height, and affixed to a rod, that can be moved by means of a micrometric screw; so that the two balls may be approximated to a distance, measurable with great precision. This latter ball, being insulated, is put into communication with the outer coating of the jar, by means of a platinum wire of a little more than a yard in length and $\frac{1}{250}$ in. in diameter, twisted round a tube, so as to render the discharges that occur between the balls * less sharp, and thus to diminish the alterations that their surface undergoes, which ought to be well polished. It is in fact necessary that these balls, which ought to be of copper, should be well rounded and polished, in order that the discharge between the outer and inner coating of the jar may always occur with the same quantity of electricity. The jar rests upon a metal foot, the communication of which with the ground is made as perfect as possible.

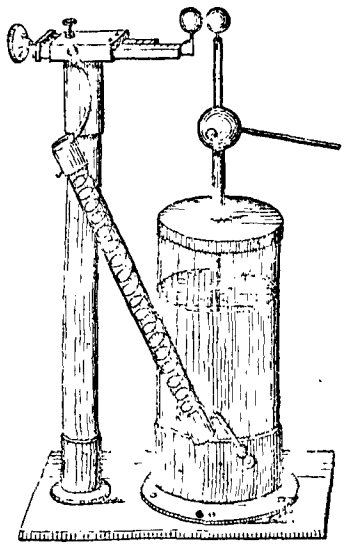

Fig. 194.

* It will not do to employ a longer and thinner wire; for the discharges, which are to be counted, would not then be sufficiently strong or distinct.

Now, in order to use the electrometric jar, the outer coating of the battery, which has been carefully insulated, must be put into communication with its inner coating; the electricity of this outer coating, which is driven into the jar, is of the same name as that with which the battery is charged, and it is proportional to it*; so that, in measuring one, the measure of the other is obtained. Now, as soon as the electrometric jar is charged with a determinate quantity of electricity, a discharge is brought about between the two balls; the number of discharges then serve as a measure of the quantity of electricity introduced into the battery. In order that these discharges shall correspond with equal quantities of electricity, it is necessary that the communication between the outer coating of the battery, and the inner coating of the jar shall be well established and continuous, and that the rotation of the glass plate of the electrical machine, by which the battery is charged, shall occur with as uniform a velocity as possible. Care must also be taken to bring the balls of the electrometric jar very close together, so that the discharges may occur with very inconsiderable quantities of electricity, which renders the application of the principle, that serves as the basis of this means of measuring, more accurate. The size q, that expresses the quantity of electricity with which the battery is charged, has therefore for a unit the quantity of electricity which, being conducted into the battery, produces a discharge of the electrometric jar; but as this unit is very feeble when the two balls of the jar are placed, for instance at a distance of $\frac{1}{25}$in. apart, we take for a unit the quantity of electricity, that corresponds to *two* discharges.

Besides the *quantity* of electricity, it is essential to know its *density*, which depends upon the extent s of the inner coating of the battery, or, which comes to the same thing, of the number of equal jars of which the battery is composed.

* The method is based upon the principle of condensed electricities (Vol. I. p. 530.); namely, that if the quantity 1 of electricity arriving at the battery developing m, in the outer coating, gives rise to a discharge of the electrometric jar, u discharges, arising from $u\ m$ of electricity in the outer coating, correspond to the quantity u, of electricity, arriving at the battery.

For the same quantity of electricity, this density is the inverse of the said extent or number, so that it may be expressed by the fraction $\frac{q}{s}$. The density may be determined directly, by means of a weight-electrometer (*fig.* 195.) formed

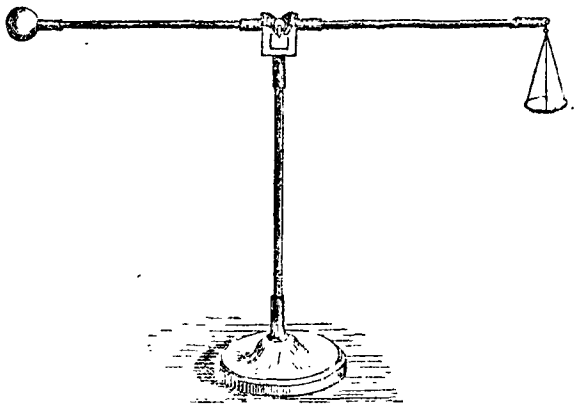

Fig. 195.

of a rod of glass 13 inches in length, furnished at its centre with an arrangement of two pivots which rest upon two agate planes, like the beam of a balance. At one end of this rod is fixed the scale-pan of a balance; at the other, a hollow metal ball $\frac{2}{3}$ in. in diameter. The beam would naturally have a horizontal direction; it is so placed that the ball by which it is terminated, shall be immediately beneath a rather larger ball, that is in communication, by means of a good conductor, with the inner coating of the battery, and shall at the same time be in contact with it. Into the scale-pan is placed a weight p, and the battery is charged, until the fixed ball repels that of the weight-electrometer, which was in contact with it. The number of discharges of the electrometric jar indicates what was the quantity of electricity necessary to bring about this repulsion, and consequently, to be in equilibrium with the weight p. But the repulsive effect is proportionate to the electric reactions or densities of the two balls, which are the same, namely $\frac{q}{s}$ for each; we have there-

fore : $p = a\left(\frac{q}{s}\right)^2$, a being a constant quantity; whence we deduce $q = s\,b\,\sqrt{p}$, b being a constant equal to $\frac{1}{\sqrt{a}}$. By taking the mean of all the calculated values, we find $b = 2.236$. Then comparing the values of q, calculated by this formula, with its observed values, we find them in perfect accordance; which proves that the density is very exactly expressed, by making it equal to $\frac{q}{s}$. This same weight-electrometer may serve as a discharging-apparatus, with a slight modification in its construction, which consists in placing the movable ball between two fixed balls, one communicating with the outer, the other with the inner coating of the battery, so that the movable ball, which is itself in communication, by means of the movable metal rod, with the outer coating, is repelled by one of the fixed balls and attracted by the other, to the distance necessary for the discharge to occur.* (*Fig.* 196.)

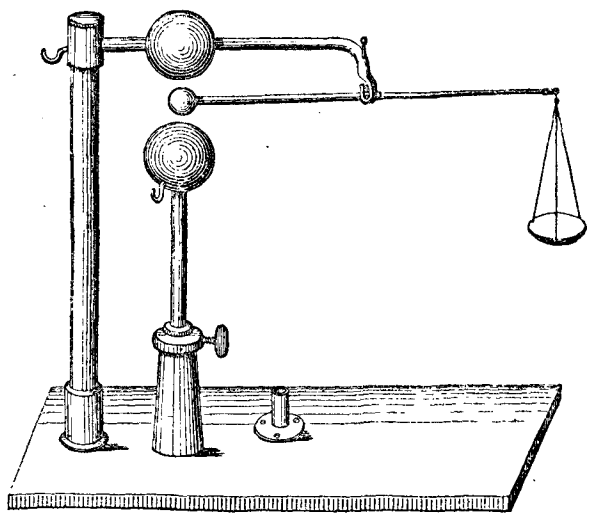

Fig. 196.

* These pieces of apparatus, with some slight modifications, are the same as those described in Vol. I. p. 118.

Now, in order to operate, the battery, the discharging apparatus, the electrometric jar, and the electric thermometer are so arranged, that the discharge, whose power is measured by the jar, traverses the wire of the thermometer. The universal discharger (*fig.* 197.), is also placed in the circuit,

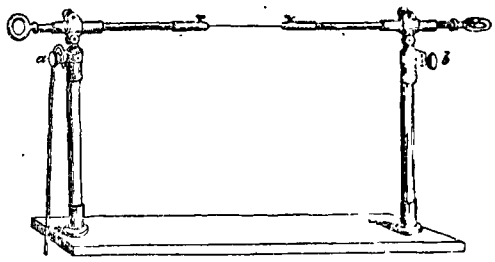

Fig. 197.

in order that other wires, besides the one that is heated in the thermometer, may be introduced. Care is taken to count the numbers of discharges of the electrometric jar, until the moment when the charge of the battery attains to the point required, in order that the discharger shall act. It is better in very delicate experiments to employ a discharger (*fig.* 198.) which is made to act in a direct way, by drawing a silk cord, attached to the arm of the lever, when the battery has been charged with the necessary quantity of electricity.

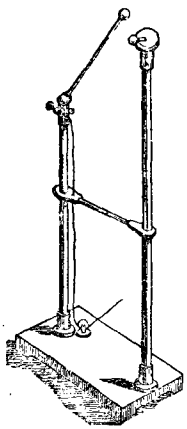

Fig. 198.

The experiments were made with a battery, whose number of jars varied from 2 to 25, each jar presenting about $1\frac{1}{2}$ sq. ft. of surface. The quantity of electricity accumulated in the battery was indicated by the number of sparks of an electrometric jar, the balls of which were one line distant from each other. The numbers given by the electric thermometer are in perfect accordance with those, which would be given by the formula $\mathrm{T} = b\,\frac{q^2}{s}$, in which T expresses the elevation

of temperature, experienced by the wire of the thermometer, q, the quantity of electricty, s, the surface of the battery, and b, a constant, that depends upon the electric thermometer. Hence is deduced the law that *the elevation of temperatures experienced by a wire, placed in the circuit of the discharge of a battery, is proportional to the product of the quantity of electricity by the density* $= q \times \frac{q}{s}$; or, which comes to the same thing, *to the square of the quantity of electricity accumulated in the battery, divided by the extent of the battery.*

Now the question is to determine the influence of the dimensions of the wire upon its heating, the circuit of the battery remaining constant. With this view, platinum wires of different lengths, coiled into helices, are successively introduced into the globe of the electric thermometer, and a battery is employed, consisting of 5 of the jars of $1\frac{1}{2}$ sq. ft. of surface. By an extensive series of experiments the heating of each wire corresponding to different values of q is found, whence is deduced the value of this heating for $q = 1$ and $s = 1$. The following is the Table of this value for different lengths of wire.

Lengths of Wire.	Heating of Wire.
11 in.	0·238
$8\frac{1}{2}$	0·228
6	0·239
$3\frac{3}{4}$	0·237

It follows from this, that the heating, that a platinum wire undergoes by the electric discharge, is independent of its length. To arrive at this result, care must be taken, when operating with shorter wires than the first, to introduce into the circuit a similar wire, but of such a length that the sum of the two wires placed at the same time in the circuit shall be always the same. In this way, there is no difference in the resistance opposed to the discharge, nor yet in its duration, for each experiment; if this precaution is not taken, the longest wire becomes a little less heated, because there operates on the time of the discharge, a greater retardation than that resulting from the interposition of the short wire

unless we at the same time compensate for the difference by the means we have just pointed out. It is the same for the determination of the law relating to the influence of the diameters of the wires; it is necessary, in this case, to operate with two wires of different diameters; one of which is placed in the thermometer, and the other elsewhere in the circuit; then, after certain experiments made in this way, the respective places of the two wires are changed, and fresh experiments are made. The resistance of the circuit thus remains the same, in each series of experiments, which causes the time of the discharge to remain the same for each of the wires, whose heating we desire to determine. In this manner by comparing the wires two and two, we find: —

Radius of the Wire in Lines.*	Heating.
0·029690	0°·1588
0·023012	0 ·3194
0·058304	0 ·0592
0·036170	0 ·3775

If the values of the heatings are compared with those of the radii, it is found that they are inversely as the fourth powers of these radii. This law would give, in fact, for the heating of the first wire, calculated according to that of the second, 0·155 instead of 0·158; and for that of the third, calculated according to that of the fourth, 0·0589 instead of 0·0592.† The differences between the result of calculation and that of observations may be altogether neglected in such experiments as these. We may, therefore, consider the following law as being well established: *When the same quantity of electricity, completely discharged in the same interval of time, traverses wires of the same nature, but of different diameters, each wire experiences an elevation of temperature, independent of its length, and inversely proportional to the fourth power of its radius.*

This law proves to us first, that each wire receives, by

* These radii have been determined with very great care, under a compound microscope of a magnifying power of 190, by aid of a micrometer, that detected the ten-thousandth part of an inch.

† These calculations were made by means of logarithms.

the same discharge, a quantity of heat proportional to its length; or, in other words, that each of its points is equally heated; which might in the outset appear reasonable, for there is always in the circuit a wire of a constant length, of which a portion only of greater or less length is contained within the globe of the electric thermometer, which is heated in proportion to the length of this portion. The law shows us, in the second place, that the wire receives by the discharge a quantity of heat that is in inverse ratio to the square of its radius, which is a proof that the influence of its size does not consist simply of the fact that, as the mass of wire to be heated being more considerable, there must result to it a less temperature; but also of this, that by the effect of its larger diameter, the electricity, in traversing it, deposits in it an absolute quantity of heat less in amount; the two influences, each depending separately on the volume of the wire, their combined action must be proportional to the square of the section, or to the fourth power of the diameter.

In the law that we have been putting forth, the quantity of electricity transmitted is always the same in the same time: we have now to determine the influence that is exerted on the heating of an invariable wire, by a difference in this quantity, or, which comes to the same thing, the variable dimensions of another wire placed in the same circuit, the length and diameter of which are made to vary. Experiments demonstrate that the heating of the invariable wire is inversely as the length of the added wire and in proportion to the square of its radius: now, this is exactly the law which regulates the electric conductibility of the wire; whence we may conclude that the heating of the invariable wire is inversely as the resistance which the discharge encounters, or reciprocally in proportion to its duration. This last conclusion is deduced from the observation which demonstrates, that the more we increase the resistance that is encountered by the discharge, by introducing into its circuit either a very long wire, or a tube filled with water, or a small cylinder of moist wood, the

less is the wire heated; it ends even by no longer becoming heated at all, and a very great quantity of electricity may traverse it without in any way affecting the liquid indicator of the thermometer. But then the discharge is no longer instantaneous; it lasts for an appreciable interval of time; and if we suppose that the retardation it undergoes is proportional to the resistance of the conductor introduced; and consequently, in the case of an homogeneous wire, to its length, we find that the values of the heating, calculated according to a formula based upon this supposition, are perfectly in accordance with the observed values. The same accordance exists between calculation and observation, when wires are introduced, whose diameter and not length is variable; if indeed we admit that the retardation is inversely as the square of the radius, which enables us to lay down the law, as follows: —

The heating of a wire by an electric discharge is reciprocally proportional to the duration of the discharge; the retardation, that the discharge encounters by the insertion of a wire in the circuit, being itself in direct ratio to the length of the wire, and in inverse ratio to the square of its radius.

By uniting in one all the laws that we have been establishing, we are led to the following more general one: —

The elevation of temperature of the normal section of an homogeneous wire inserted in the circuit of a battery is in inverse ratio of the fourth power of its radius, and in direct ratio of the quantity of electricity accumulated, divided by the time of the discharge: $T = \frac{a}{r^4} \times \frac{q}{z}$, a being a constant, that depends on the nature of the wire, r the radius of the wire, q the quantity of electricity, and z the time of the discharge.* We see that

* When a very fine wire is introduced into the electric thermometer, and the charge of the battery is gradually increased, diminishing at the same time the number of jars, it is observed, even when the total quantity of electricity does not change, that the heating of the wire goes on increasing, and that the wire itself suffers deflections and finishes by being altogether crimpled,—a deformation that cannot be made entirely to disappear, except by incandescence and polishing. This increase of effect produced by the same quantity of electricity, but of increasing density it is true, can only be attributed to an increase in the rapidity of the discharge, and the most simple supposition to

the length of wire enters neither into the law nor into the formula; which is a consequence of the law, relative to length, which we established further back; since, as we have remarked, the influence of length is not felt, except on the duration of the discharge, of which z is the expression. The formula, that gives the value z, includes the length of the wire introduced into the circuit; but this formula, which is a little complicated, does not give for z a value o, when the length of wire becomes o. This result, which is a little odd at first sight, is explained, however, when we reflect that the circuit is not composed of wires only, but of the points of connection of these wires, which subsist always; so that the time given by the formula, when the wire is reduced to a length of O, is that which the discharge requires for traversing the invariable parts of the apparatus, and the junction pieces by which they are connected together; it is this time which is taken for unity.

The heating of a wire is also influenced by interruptions in a circuit, such as those which result from the interposition of a stratum of air, of a sheet of paper of a greater or less thickness, or of a plate of glass or mica between the two extremities of the discharger, between which the discharge must pass; and experiments lead to the following results: *the electric discharge heats the wire that it traverses less, in proportion as the electricity must pass over a greater obstacle before the discharge sets out.* We are not here referring to an obstacle that retards the discharge continuously, which would

admit is, that the time of the discharge is inversely proportional to the density of the electricity. By calling y the density, determined by the tension balance of the weight-electrometers, if the quantity 1 of electricity is discharged in the time $\frac{1}{y}$ the quantity q will be in the time $\frac{q}{y}$; consequently z, the time of the discharge of the battery, is proportional to $\frac{q}{y}$. But we have seen that y the density, is equal to $\frac{q}{s}$; therefore, $z = \frac{q}{y}$ will be equal to $q \times \frac{s}{q} = s$. Whence it follows, that in the formula $\mathrm{T} = b, \frac{q^2}{s}$, we may put z in place of s, and express $\mathrm{T} = b\,\frac{q^2}{z}$.

constitute a bad conductor; but to an obstacle which, so long as it is not surmounted, renders all transmission of electricity impossible. . But, as the heating depends at once upon the quantity of electricity and upon its velocity, and as the quantity is not sensibly diminished by the presence of the obstacle, we must hence conclude that the obstacle, although it is surmounted, increases the duration of the discharge.

Finally, an important circumstance, to which we must have regard in the heating of a wire by the discharge, is the influence of inductive currents, which may be developed in conductors that are near those which are traversed by the discharge. Riess has made a very detailed study of this influence also, by placing in the circuit a connecting wire coiled into a spiral, and near this spiral another wire independent of the battery, coiled also into a spiral, or simply a thin plate of tin, interposed between two plates of glass. The effect of this exterior conductor upon the calorific power of the discharge is felt only so long as its conductibility is inferior to that of the connecting wire; and experience shows that then *the discharge is more retarded, and consequently the heating of the thermometric wire is less in proportion as the conductibility of the exterior circuit is less.* However, the diminution in the heating in the principal circuit, which results from the increase in the resistance that is presented by the closed secondary circuit, has a limit to which we arrive by increasing the length of a german silver wire, for instance, which forms part of this circuit. The two similar spirals, both formed of a copper wire ·058 in. in diameter, and 166 in. in length, one of which forms part of the principal circuit, the other of the secondary circuit, are placed at $\frac{1}{13}$ in. from each other; the german silver wire that connects the two extremities of this second spiral is 374 in. in length; the heating experiences a diminution of 52 per cent.: this is the maximum of diminution. For more considerable lengths, the heating approaches to what it was at the first; and, when the german silver wire is about 623 ft. in length, the diminution of heating is not more than 13 per cent. The diminution of heating depends not

only upon the conductibility of the secondary circuit; it is also very much influenced by that of the principal circuit, and particularly by the resistance that is opposed to the passage of electricity by the platinum wire of the thermometer, on account of its tenacity. Thus, if we pass the discharge through a shorter and larger platinum wire which is placed in the axis of the helix of a Breguet's thermometer, it is found, by means of the indications of this thermometer, that the diminution of the heating may attain, under the influence of the secondary circuit, to 86 per cent. of the primitive effect that was obtained, when the secondary circuit was not in existence, or was not closed.

In all these experiments, the secondary circuit acts merely in consequence of its conducting properties; for exactly the same effects are obtained by substituting for the german silver wire one of platinum, that opposes the same obstacle to the passage of the electricity.

The preceding facts confirm what we have said respecting the duration of the discharge. In fact, the current produced by induction in the secondary wire, although a little in arrear in respect to the commencement of the discharge, nevertheless reacts upon a portion of this discharge, retards its movement, and consequently diminishes its heating power. The prolongation of the circuit has the double effect, in the first place, of retarding the induced current, and by that increasing its reaction upon the principal wire; in the second place, of weakening this current, and on the other hand of diminishing the same reaction. At first, the former effect predominates, and the reaction is seen to be increased; but the secondary current is soon so much weakened that its influence disappears more and more until it becomes null for a certain length; which is equivalent to a complete interruption of the circuit. However, we shall not insist further upon this particular point, which is connected with the properties of induced currents, a subject that we have already discussed in detail *, and to which we have reverted in this place only on

* Vol. I. p. 403. and following pages.

account of its showing to us, under another form, the remarkable influence of the duration or the velocity of the transmission of electricity upon its calorific power.

Finally, we shall not dwell longer upon a class of phenomena which show, under another form, the remarkable influence, that is exerted upon the heating by the density and the duration of the discharges. These are the calorific effects, that are obtained with Franklin's batteries, which consist of a series of Leyden jars, placed in communication one with the other, so that the knob of the first communicates with the conductor of the electrical machine, the knob of the second with the outer coating of the first, and so on.* The heating of the wire produced by the discharge of a battery of this kind, led Riess, at the end of a great number of experiments, to remarkable results, in respect of density, possessed by the electricity in the various jars of which it is composed, and of the influence of the density.†

After having set forth the general laws which regulate the heating brought about by discharges in good conductors, it remains for us to examine what is the influence upon this heating, of the particular nature of these conductors, which in our experiments are wires. It is to Riess we are also indebted for having, by his very numerous and accurate experiments, determined this influence. This determination was made for each wire by means of two experiments: in one, the wire submitted to the test,— for example a wire of lead, — was placed in the circuit of the discharge, in which was also included the platinum wire of the electric thermometer; in the other, the leaden wire was in the thermometer, and the platinum wire of the thermometer in the circuit. Hence it was easy by means of the laws already established, and by taking account of the diameters of the two wires, to deduce the heating of the leaden wire, in comparison with that of platinum; the operation was carried on in the same way for each of the other wires, and the following Table was obtained: —

* *Vide* Vol. I. p. 115. *fig.* 58.

† *Vide* the final note D, for the details relative to the laws of the heating of wires by electric discharge.

Metals.	Force of Retardation.	Power of Heating.	Quantities of Heat liberated.
Silver - -	0·1043	0·1267	0·1120
Copper - -	0·1552	0·1133	0·1447
Gold - -	0·1746	0·2112	0·1847
Cadmium - -	0·4047		
Brass - -	0·5602	0·3861	0·5616
Palladium - -	0·8535		
Iron - -	0·8789	0·7080	0·9148
Platinum - -	1·0000	1·0000	1·0000
Tin - - -	1·0530	1·5700	0·8917
Nickel - -	1·1800	0·8727	1·1820
Lead - -	1·5030	2·8760	1·4550

The comparison that may be made between the two kinds of values for the same metal, that are contained in the first two columns of the above Table, shows that there is no direct relation between them. But we arrive at a more satisfactory result, by transforming the numbers of the second column, which express the relative elevations of temperature, into relative quantities of heat. For this purpose we must multiply each of these values by the specific heat and density of the metal to which it refers, and divide the product by the product of the specific heat and density of platinum, which is always taken as unity. We thus obtain the relative quantities of heat developed by the electric discharge in each metal, that developed in platinum being taken as unity; the third column of the above Table contains these values. We see that they differ very little from the numbers that express the force of retardation, so that this force and the quantity of heat developed in a metal may be regarded as proportional to each other; and when the first of these two values has been determined for a metal, which is always an easy matter, we may readily deduce from it the second, and consequently the power of heating of the metals. The following is the general rule: —

The relative power of the electric heating of a metal is found, by dividing its force of electric retardation by its specific heat and by its density.

It follows, from the combination of all these various laws,

that we may express, by a general formula, the quantity of heat liberated in each of the wires, which, connected end to end, compose a chain through which the electric discharge passes. This formula leads to the following principle.

In wires of any metal, connected in succession one to the other, and which serve at the same time to discharge an electric battery, quantities of heat are liberated, which are exactly proportional to the retardations that each of these wires taken separately would produce in any electric discharge. This general principle and the formula that has led to it, are equally applicable to the most simple case, that of a single wire placed in the circuit; and we thus obtain the quantity of heat liberated in the wire.

If the wires, that are placed successively one after the other in the circuit of the battery, are of the same diameter, and lengths are given to them that are in the inverse ratio of their force of retardation, the formula indicates the same quantity of heat from each of them, provided the accumulation of electricity in the battery is the same. Thus, supposing that an electric battery is discharged successively with wires of the same diameter and different natures, whose lengths are for each metal inversely as its force of retardation, and represented consequently by the numbers of the Table, that follows,—namely, for instance, 148.7 inches for the silver wire, 88·8 for the gold wire, 15·5 for the platinum wire,—we shall, it is true, find that all these wires, by the effect of the discharge, suffer very different elevations of temperature; but that if we suppose them surrounded by ice during the experiment, they will have melted, in order to return to their primitive temperature, exactly the same quantity; that is to say, the total quantity of heat liberated in each of them would have been the same; which explains why their temperature is more elevated in proportion as they are shorter.

Table of the inverse values of the force of retardation, this force being 100 *for copper.*

Silver	148·7
Copper	100·
Gold	88·87

Cadmium	38·35
Brass	27·70
Palladium	18·18
Iron	17·66
Platinum	15·52
Tin	14·70
Nickel	13·15
Lead	10·31

Laws of the calorific effects, produced by the passage of continuous currents through good conductors.

The results obtained by Riess have had the valuable advantage of determining in a rigorous manner this dependence, which long before his time had been recognised to exist between the calorific effects of dynamic electricity on the one hand, and the quantity and velocity of this electricity on the other. It was while studying the calorific powers of the voltaic current that this dependence was discovered, without its laws, however, having been exactly established. Thus I had already shown in 1830 that the reason for which a pile with large surfaces, composed of numerous pairs, was preferable to a pile formed of a great number of pairs of less surfaces, for the development of heat in wires placed in their circuit, was that the current in the former case had a greater velocity, and that it was necessary, in order that the calorific effect should be at its maximum, that the resistance of the pile should not exceed that of the wire placed between its poles. More recently, I showed that the calorific effect diminished with the intensity or velocity of the electricity in a much greater proportion than this intensity or this velocity. For this purpose, having placed the helix of a Breguet's thermometer* in the circuit of a pile of 8 pairs of zinc and copper, each presenting a surface of 41 sq. ft., and which were charged with a mixture of 40 parts water, 2 of sulphuric, and 1 of nitric acid, I passed the current through a certain extent of concentrated nitric acid, placed in a prismatic glass trough and which might be separated into two or more compartments

* Vol. I. p. 33. *fig.* 21.

by means of platinum diaphragms. A magnetic galvanometer constructed with stout wire was also in the circuit. The following are the results: —

Number of Diaphragms.	Magnetic Galvanometer.	Calorific Voltameter.
1	85	312°
2	84	176
3.	83	115
4	75	12
5	40	0
6	37	0

By interposing into the circuit a chemical instead of a magnetic voltameter, the following results are obtained: —

Number of Diaphragms.	Chemical Voltameter.*	Calorific Voltameter.
0	5″	38°
1	25	3

* The number of seconds indicates, for the chemical voltameter, the time necessary for obtaining a given quantity of gas; it is therefore inversely as the chemical power of the current.

Thus the reduction of the calorific effect to $\frac{1}{13}$ corresponds to a reduction of only $\frac{1}{5}$ of the chemical effect. By supposing, therefore, that either the magnetic effect or the chemical effect are in a simple relation with the intensity and the velocity of the current, we see in what greater proportion the calorific effect diminishes or increases with this intensity or this velocity.

Before going further, let us observe that there is in the calorific effects of dynamic electricity an important distinction to be made between the case of discharges and that of continuous currents. In the former, the velocity, for a given quantity of electricity, depends only upon the conductors that form the arc for joining over the battery, and upon the extent of its surface; in the latter, it further depends upon the very construction of the producing apparatus. And, in fact, when this apparatus is a voltaic pile, the latter forms a part of the circuit traversed by the current; as well as the wire that is heated, and all the conductors by which the two ends of this wire are connected with the poles; whilst with a

battery of Leyden jars the same is not the case. Another difference, which renders all comparison difficult, is that the discharge must be instantaneous, whilst the current has a certain duration, such that the slow escape of the same quantity of electricity does not produce the same calorific effect, as when this electricity, instead of coming from a pile, is derived from an electric machine or a Leyden battery.* Nevertheless, as we are about to see, some of the laws by which calorific phenomena are regulated, when they are produced by a continuous current, are the same as for the case in which they derive their origin from discharges. This is derived from the researches of three philosophers, Joule, Lenz, and E. Becquerel.

Joule measures the quantities of electricity by a tangent galvanometer, which he places in the circuit; he then transmits the current through a copper wire, which he passes into a glass tube, and then twists in a helix around this tube, which is itself placed in a vessel containing a certain quantity of water. The following is then the Table of the results: —

Deviation of the Galvanometer.	Quantities of dynamic Electricity.*	Heating of Water in half an Hour.	Relations between the Squares of the Quantities of Electricity of Column No. 2.
16°	0°·43 Q		
31½	0 ·92 „	3°	2·9
55	2 ·35 „	19·4	18·8
57⅔	2 ·61 „	23·	23·2
54½	2 ·73 „	25·	25·4

* M. Joule takes for the unit of measure of the quantity of dynamic electricity a quantity capable of decomposing a hundred grains of water per hour; it is produced by a current capable of deflecting his galvanometer, 35°·5. It is this unit that M. Joule calls Q.

The experiment prolonged for an hour gave a result in accordance with that contained in this Table; which proves that the heat, liberated by the current in its passage through the wire, is truly proportional to the square of the electric intensity. On the other hand, certain experiments made with wires of different natures, namely a copper wire, an

* We shall return to these differences when engaged upon the incandescence of wires, on phenomena in which they are especially sensible.

iron wire and a filament of mercury, contained in a twisted glass tube, had proved to M. Joule that the same current transmitted through two of these different conductors, placed one after the other, produced quantities of heat which were for the copper wire, compared with the iron wire, 5·5 : 6; and for the copper wire, compared with the filament of mercury, as 2·9 : 4·4. These relations were precisely those which direct experiment shows to exist between the electric resistances of the conductors employed. Whence may be deduced the following general law, that *when a current of voltaic electricity is propagated along a metal conductor, the caloric liberated in a given time is proportional to the resistance of the conductor, multiplied by the square of the electric intensity.*

M. E. Becquerel perfected Joule's method, by taking account of the cooling that had occurred during the continuance of the experiment, and by employing for this purpose a calorimeter, in the waters of which were plunged a very sensitive thermometer, and a wire twisted into a spiral, which was traversed by the current.* The quantity of electricity was here measured by the quantity of gas liberated per minute in a voltameter, which was brought to 0° and to ·04 in. of pressure: this quantity was made to vary by producing the current from a greater or less number of pairs of a constant force.

Three principal experiments have been made according to this method: one with a copper wire, a yard in length and ·017 in. in diameter; the second with a platinum wire 17 $\frac{1}{4}$ in. in length, and ·009 in. in diameter; and the third with a platinum wire 2·78 ft. in length, and ·039 in. in diameter. Each of these wires was twisted into a helix around a glass tube. If, in each of the three series of experiments, we divide the quantities of heat, measured by means of the calorimeter, by the square of the corresponding quantities of electricity, measured by means of a chemical voltameter, we obtain as quotients numbers that are very little different from

* This method, in which account is taken of the heat lost by cooling during the continuance of the experiment, is the same as that which La Roche and Bérard adopted for the determination of the specific heat of gases.

each other, for each of the experiments of the same series,—numbers whose mean is for the first series, composed of six experiments, 0·0340; for the second series, composed of five experiments, 0·1844; and for the third series, composed of four experiments, 3·143. These results prove, first, that the quantity of heat liberated by the passage of the current is proportional to the square of the quantity of electricity that passes; moreover, the three numbers above being the expression of the quantity of heat liberated by the passage of the same quantity of electricity, it is easy to recognise that they are in the direct ratio of the resistance that is presented by the three wires to the transmission of the current. In fact, the following is a comparative Table of the quantities of heat liberated, deduced both from experiment and from calculation based upon this hypothesis :—

Wires.	By Experiment.	By Calculation
Fine platinum wire	3·143	3·143
Thick „ „	0·187	0·177
Copper wire - -	0·034	0·038

Finally, Lenz arrived at the same results as Joule and E. Becquerel, by placing the wire, that is heated by the current, in spirits of wine,—a still more imperfect conductor than pure water, which gives greater assurance that no portion of the current traverses the liquid, and which consequently is transmitted entirely through the wire; a certainty that is not attained with water. In *fig.* 199. B represents the glass stopper of a jar, filled with spirits of wine; this stopper is pierced by two holes, which allow of the introduction of two thick metal conductors, that are placed at S, in communication with the poles of a pile; and the inner ends of which are united by a fine wire coiled into a helix, which is to be heated by the current. A tangent-galvanometer and a rheostat, intro-

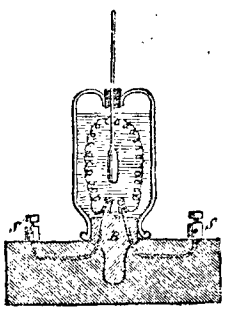

Fig. 199.

duced into the circuit, serve to measure the current and to reduce its force to the standard desired in each experiment. The following Table contains the results of sixteen experiments made with three wires of german silver of different thicknesses, with wire of platinum, of iron, and of copper.

Nature of the Wires.	Force of the Current.	Time of heating Spirit of wine 1°.	Resistance of the Wire to Conductibility.
German silver,			
No. 1. - -	6·93	1·349	93·50
do.	10·53	0·571	93·63
do.	14·30	0·300	93 94
German silver,			
No. 2. -	10·53	0·920	58·76
do.	14·30	0·481	58·64
do.	18·32	0·288	59·01
do.	14·30	0·457	60·16
German silver,			
No. 3. - -	18·32	0·384	44·59
Platinum - -	14·30	0·555	50·45
do.	18·32	0·325	51·41
Iron - - -	22·69	0·435	24·92
Copper - -	18·32	1·301	13·90
do.	22·69	0·385	13·90
do.	27·52	0·575	13·92
do.	32·98	0·381	14·01
do.	27·52	0·544	14·31

According to this Table, we perceive that, for each wire, the resistance to conductibility increases slightly with the force of the current, or rather with its heating; which ought to be the case, since elevation of temperature diminishes the electric conductibility of metals.

It is easy to deduce, from the number contained in the above Table, the different laws of the heating of wires by the electric current. First we see that the time t, employed by two different wires, traversed by the same current, for heating the same quantity of spirit of wine 1°, is the inverse of the resistance l, to conductibility of these two wires; and consequently that the heating itself is proportional to this resistance. In fact, we have $t \times l$ constant in all the experiments made with a current of the same force. The

following are the values of this product for different currents:—

With the current of 10·53.

First german silver wire - - -	$t\,l = 53{\cdot}46$
Second „ - - -	$t\,l = 54{\cdot}06$

With the current of 14·30.

First german silver wire - - -	$t\,l = 28{\cdot}18$
Second „ - - -	$t\,l = 28{\cdot}11$
Third „ - -	$t\,l = 27{\cdot}49$
Platinum wire - - -	$t\,l = 28{\cdot}00$

In like manner, we shall find $t\,l$ constant in four experiments with the current of 18·35; and in two with the current of 22·69. The small differences between the values of $t\,l$ in each case arise only from the inevitable errors of experiment.

The numbers of the Table show also that the heating is proportional to the square of the force of the current; or, which comes to the same thing, that this square is the inverse of the time t of the heating of 1°; namely, that $s^2\,t$ is constant for each of the six wires, employed successively in the experiments. The slight differences that are presented between the value $s^2\,t$, for each wire, are due to the fact that the more rapid the heating is, the less is the loss of heat arising from cooling; so that t is necessarily smaller than it would be in the case wherein the current is more powerful. Thus, if we take for example the experiments made with the first wire of german silver, we find for $s^2\,t$ the following values: 1st, 64·8; 2nd, 63·3; and 3rd, 61·3, which, as we see, go on diminishing. It is the same for the different values of $s^2\,t$ with each of the five other wires. In order that these values should be quite equal with each of the wires, it would be necessary to take account of these differences in the influence of cooling.

Whatever be the case, we shall always find the two same laws; namely, that the heating is proportional, 1st, to the resistance of the wire to conductibility; 2nd, to the square

of the force of the current. These two laws combined ought to give as constant, in all the experiments of the above Table, the product $s^2\ t\ l$, since t is the inverse of the heating. Now, the products $s^2\ t\ l$, deduced from the number furnished by the sixteen experiments of the Table are sensibly equal, and their mean value is 5856.

The induction currents, engendered by rotation before the poles of a magnet of an armature of soft iron surrounded by a wire, present, with regard to their calorific effects, the same laws as the currents of discharge and voltaic currents. Joule has also demonstrated, by plunging into water, furnished with a thermometer, the soft iron armature and the bobbins of wire with which it is surrounded, that the heat developed in the wires themselves of the bobbins is proportional to the square of the intensity of the current.

A third law to be added to the two others is that, whatever be the length of a conducting wire, if it transmit the same quantity of electricity in the same time, the elevation of the temperature of each of its points is the same. Only if its length increases, the source of the current must be rendered more energetic, in order that the same quantity of electricity shall pass in the same time; so that the deviation of a galvanometer remains the same. This law was proved for the first time by Peltier, and confirmed by E. Becquerel.

The three laws that we have established for a continuous current are the same as those which Riess had found for the case of the discharge*, however, there is between these two modes of heating by electricity an important difference, which renders all comparison between them very difficult; it is the duration of the former, and the instantaneity of the latter. It would be in vain to accumulate on a battery a quantity of electricity equal to the whole of that which pro-

* M. E. Becquerel had thought he had found that, for currents as well as for discharges, the elevation of temperature is in inverse ratio of the fourth power of the radius of the wire; but this law does not yet appear to us to be sufficiently firmly established to enable of its being admitted. We shall see this hereafter.

duces a current capable of heating a wire for a minute; yet on making this electricity gradually pass away for the period of a minute, the same amount of heating would not be produced. We know besides that, in the instantaneous discharge, the same quantity of electricity produces a calorific effect, that varies with the surface of the battery. The cause of these differences lies in the nature, so different itself, of the two sources of electricity, as we shall see, when we shall have studied these sources.

An important point in the researches that have been engaging our attention, is to know what the influence is of the heating itself, that the wire undergoes, upon the resistance that it opposes to the electric current. We have, in fact, seen that this resistance increases with the elevation of temperature due to an exterior cause; now, here the heating arises from the resistance of the wire; and, on the other hand, this resistance increases with the heating: where is the limit, and how is equilibrium established?

This question has been treated in detail, and resolved by means of a great number of experiments, by M. Romney Robinson. The instruments of which he made use are, a galvanometer, a rheostat, and a very sensitive pyrometer, of the nature of the one we have described*, and by means of which he was able to appreciate the variations of temperature of a wire, especially of one of platinum. The following is a Table of the results obtained with a platinum wire ·078 in. in diameter, and a pile composed of a greater or less number of pairs. The force of the current is deduced from the indications of the galvanometer, the current taken for unity being that which producing on the galvanometer a deviation of 45°, liberates in a voltameter 6·57 cub. in. of gas in five minutes. The pyrometer gives the temperature of the wire.

* Vol. I. p. 32. *fig.* 19.

Force of the Current.	Temperature of the Wire.	Resistances of the Wire in turns of the Rheostat.
0·809	289·7	305·5
0·858	319·9	320 8
0 957	559·3	385·2
1·168	930·9	497·9
1·214	1020·6	523·8
1·357	1215·0	591·6
1·404	1338·7	643·8
1·515	1447·0	666·4
1·538	1545·6	706·2
1·794	1761·9	734·4
2·089	1966·4	793·9
2·200	2116·0	840·5
2·222	2166·2	827·8
2·318	2461·6	898·2

It is curious to see how the resistance increases in a rapid progression with the temperature; for at 289°·7 it is equivalent to 305·5 degrees of the rheostat; and at 2461°·6, to 898·2.

On placing the pyrometer in vacuum, the increase of resistance with the temperature is the same, only the force of the current, necessary to produce the same temperature, is a little less, because the absence of the surrounding air diminishes the cooling.

The following is a Table of similar experiments made with a wire of ·157 in. in diameter. We should remark that the eighth experiment was made by plunging the pyrometer into diluted alcohol, so that the temperature of the wire could not rise above that of the boiling of this liquid, namely, 207° Fahr., nearly that of the boiling of water.

Force of the Current.	Temperature of the Wire in degrees Fahr.	Resistances in Degrees of the Rheostat.
1·522	365·9	127·8
2·020	481·3	144·9
2·411	719·6	169·0
2·758	1020·7	212·0
3·226	1310·4	238·7
3·699	1518·0	270·1
4·352	1883·9	318·6
9·548	2078·0	393·8
4·821	2206·7	346·0
5·230	2355·1	351·4

The eighth experiment, included in this Table, demonstrates, that the increase of resistance is not due to the increase of the intensity of the current, since the current there is six times stronger than in the first experiment, and the wire presents less resistance; but that it arises from the elevation of temperature, which on account of the surrounding alcohol, is much less in this case. It even appears to be very exactly proportional to this elevation of temperature, whether for a platinum wire, or for one of copper, these two metals being the only ones upon which Mr. Robinson has operated, because they are the only ones whose co-efficient of dilatation for high temperatures has been determined.*

The very considerable increase of resistance, which accompanies that of temperature in a wire, gives rise to the question,—to know whether the calorific effect of the current, which we have seen to be proportional to the resistance that it encounters, is proportional to this resistance, in such sort that the wire possesses it before having been heated, or to this resistance such as it exists, when the wire has attained the temperature that is imparted to it by the passage of the electricity. Mr. Robinson solved the question by enclosing a platinum wire w (*fig.* 200.) in a first glass vessel B, placed itself in a second A, filled with water; the wire is placed in the circuit by means of the conductors C, which receive the poles of the pile. The wire w is first surrounded by air; the current that traverses it, heats it very powerfully, and its resistance increases accordingly; its heat is all employed in heating the glass envelopes and the water placed between them. In one experiment, the quantity of water being $5\frac{1}{2}$ cub. in. a current of a force equal to 3·527, raised the tem-

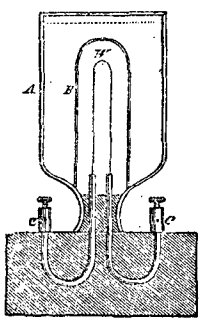

Fig. 200.

* Mr. Robinson made use of the co-efficients of dilatation given by Dulong and Petit; but he was not able to make use of the one which they have given for iron, this metal being too oxidizable for its dilatation to be accurately appreciated at high temperatures.

perature of the water from 72° to 77°·5 Fahr,. being transmitted for twelve minutes; the resistance of the wire was equivalent to 257·6 of the rheostat; the wire was red-white, and its temperature must have been about 1500°. After having allowed the apparatus to cool, a portion of the water was allowed to pass from the exterior into the interior vessel, so as to fill it completely. The current is then transmitted, which is brought to the force of 3·558, almost the same as before, by placing in the circuit an additional resistance of 165°·6 of the rheostat. The temperature rose only 2°·97 instead of 5°·5, and the increase of resistance of the wire was only 89° of the rheostat, instead of 257·6. If, in this latter case, we still operate with the same current, but without introducing any additional resistance into the circuit, its force is then 6·045; the thermometer rises to 83° 2 Fahr., and the increase of resistance is equal to 94°·5 of the rheostat. The force of the current, which has almost doubled in this case, compensates and more than compensates the effect of the diminution of resistance; whilst in the second case, the current having preserved the same intensity as the former, the heating is nevertheless much less; because the resistance is not so great, the wire being prevented by the water in which it is plunged from acquiring the high temperature, which it had in the former experiment. It follows therefore from this that the true law of the heating of the wire by a current is, that the heat liberated is proportional to the square of the intensity of the current, and to the actual resistance of the wire, (namely, that which results from its heating).

The researches of Mr. Robinson show us that, when a wire is heated by a voltaic current, its resistance to the passage of this current gradually increases until the fusion of the wire takes place, and that this increase is very exactly proportional to that of the temperature. It is therefore important to researches in which we intend to have exact measures of currents, by means of the rheostat, to take account of this cause in the variation of the resistance.

We may further remark that it is perhaps a matter of difficulty to explain the great increase of resistance, of which

we have given the numerical value, solely by the effect of the little increase of the distance of the particles, which arises from the elevation of temperature. Mr. Robinson found the cause bearing very little relation to the effect; he prefers attributing the phenomenon to the direct action of heat. However, the great elevation of temperature, experienced by the wires, producing in them a dilatation in proportion always more considerable, as they are more highly heated, it would not be astonishing that the increase of distance of their particles, that follows from this, joined to the modifications that the propagation of the current itself experiences, were sufficient to account for the increase of their resistance, without being obliged to recur to a direct intervention of heat, as we shall see in a subsequent paragraph.

The heating that is experienced by the wire, by the effect of the current which traverses it, while increasing the resistance that it opposes to the passage of this current, must therefore, in diminishing at the same time its intensity, favour its calorific effect; a double result, of which one is the converse of the other, that terminates by determining a state of equilibrium between them. But, if by an exterior cause, we cool one part of the wire that is red by the current, the other portion immediately becomes much more incandescent, and may even melt or burn; because in diminishing by cooling the resistance of a portion of the circuit, we increase the total intensity of the current that is traversing it. Davy was the first to observe this, by giving to his experiment a very striking form, which consisted in placing a piece of ice upon a portion of platinum wire made red by the current, which increased considerably and immediately the incandescence of the rest of the wire. In like manner, when this wire was made red by the current along its whole length, he had merely to heat a portion of it to red-white by means of a lamp, in order that the rest should become cold.

This influence of the causes of exterior cooling, upon the phenomenon of the incandescence of wires, gives rise, in some cases, to effects that are very inconsistent apparently, but which, nevertheless, enter into the general laws that we

have laid down:—Thus it is well known that a platinum wire becomes red much more easily, and along a much greater length, *in vaccuo* than in air; which may be easily verified, by means of the apparatus of *fig* 201. which consists

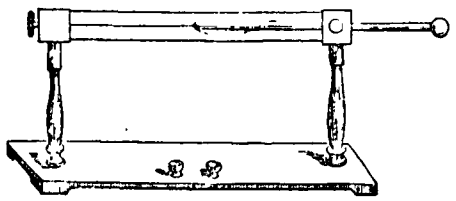

Fig. 201.

of a tube terminated at one end by a pair of brass nippers, to which one end of the wire is fixed, and at the other by a collar of leathers, in which passes a metal rod, that slides along the wire, so as to place a greater or less portion of it in the circuit. The nippers and the rod communicate exteriorly each with one of the poles of a pile. In proportion as the air is rarefied in the tube, and as vacuum is approached, we perceive that a greater length of wire may be made red.

But if, instead of having a single wire, there are two successive wires, perfectly similar in respe t o their dimensions and their nature, separated from each other by a thick conductor, then the cooling influence of the surrounding medium, produce effects that are singularly complex, and which Grove was the first to point out and to study with care. The apparatus that was employed by this learned English philosopher, consists (*fig.* 202.), of two glass tubes, about $\frac{1}{4}$ in.

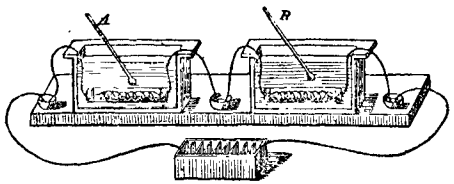

Fig. 202.

in diameter, and about $1\frac{1}{2}$ in. in length, closed by plugs traversed by small copper rods, to which are attached fine pla-

tinum wires, coiled into a helix, $\frac{1}{10}$ in. in diameter, and about 4 in. in length, when uncoiled; one of the tubes is filled with oxygen, the other with hydrogen, and they are plunged into two similar distinct vessels, each containing about $3\frac{1}{2}$ oz. of water. A thermometer is placed in each vessel; and the wires are connected so as to form a continuous circuit. A current, produced by a pile of eight pairs of Grove's, each presenting a surface of eight square inches, traverses them successively; and the platinum wire placed in the tube, which contains the oxygen, is seen to become red-white, whilst that which is in the hydrogen tube is not heated in a visible manner. Hitherto the phenomenon does not appear extraordinary; since we know that the cooling influence of hydrogen is comparatively much greater than that of the other gases. But what is singular is, that the temperature of the water is raised very unequally in the two vessels. Thus, in one experiment it rose in the vessel where the hydrogen tube was, from 60° to 70°; and in that in which was the tube filled with oxygen, from 60° to 81°, namely, double the number of degrees; analogous differences, but not so considerable, are obtained with other gases. The following is the number of degrees, to which water becomes heated, by surrounding the platinum wire successively with different gases, and associating it each time with a similar platinum wire, surrounded by hydrogen.

Hydrogen	10°·
Sulphuretted Hydrogen	10 ·8
Olefiant gas	16 ·5
Carbonic acid	19 ·8
Oxide of Carbon	19 ·8
Oxygen	21 .
Nitrogen	21 ·6

It follows from this Table that the tube in which is the gas, whose cooling power is most considerable, hydrogen, is the one that imparts the least heat to the water with which it is surrounded. Thus, not only is platinum wire unable to preserve so high a temperature in this as in the gases, which is not astonishing, seeing that it is surrounded by a medium

endowed with a greater amount of cooling power; but it moreover receives from the current a less heat, as is proved by the temperature of the water, which in each case absorbs all this heat.

Whence arises this latter effect? Is it that the gases exercise a conducting power, proper, but different for each, which would cause a greater or a less proportion of the current to traverse them instead of to pass entirely by the wire? But the study that we made in the preceding Chapter, of the electric conductibility of the gases, does not allow us to adopt this explanation.

It is to Clausius that we are indebted for having found the true cause of this anomaly, which is due to the wire's becoming a better conductor in cooling; hence the current, in traversing it, meeting with a less amount of resistance, developes in it less heat. Thus the hydrogen, in Grove's experiments, plays the same part as the ice in Davy's; it cools the platinum wire more than another gas does; by this it renders it a better conductor, consequently, less susceptible of being heated by the current, whilst at the same time it facilitates the transmission of this current; and in thus increasing its intensity, contributes to the more considerable heating of the wire placed in the other gas.

It follows from this that the more considerable the cooling power exerted by a gas, the more conductive it will render the platinum wire, at the same time it will diminish the elevation of temperature, which is produced in it by the passage of the current. Mr. Grove himself found this to be the case, by placing in the voltaic circuit, with a chemical voltameter, the platinum wire, surrounded successively by each of the gases. The following is a Table of the results:

Gas surrounding the Wire.	Quantity of Gas liberated per Minute.
Hydrogen	138·6
Olefiant gas	126·0
Oxide of carbon	118·8
Carbonic acid	118·8
Oxygen	117·0
Nitrogen	115·0

The order of the gases in this Table is perfectly the same as in the Table in which is contained the cooling power of each gas upon the platinum wire.

The laws that regulate the liberation of heat by the passage of the current through wires, is equally applicable to the case of liquid conductors, as M. E. Becquerel demonstrated, making use successively of two solutions, the one of sulphate of copper, the other of sulphate of zinc.* He took the precaution to use as electrodes, in the former case, copper wires, in the latter, zinc wires, so as to avoid chemical changes in the liquid, during the continuance of the experiment. A thermometer, plunged into the liquid, indicated its temperature, and a chemical voltameter placed in the circuit, measured the intensity of the current. Every precaution was observed, as with the wires, to take account of the cooling of the liquid, which was contained in a platinum crucible. The following are the quotients, for each solution, that are obtained by dividing the number which represents the quantity of heat liberated in each experiment, by the square of the number, that represents the corresponding intensity of the current:

Experiments.	Sulphate of Copper.	Sulphate of Zinc.
1st. Experiment -	0·2158	0·4280
2nd do. -	0·2205	0·3025
3rd do. -	0·2032	0·3190
4th do. -	- -	0·4123
Means - -	0·2132	0·3654

The very sensible equality of these quotients, in each series of experiments, notwithstanding several deviations, due to the difficulties of the experiment, especially sensible with sulphate of zinc, very well shows that *for the same liquid, the quantity of heat is proportional to the square of the intensity of the current.*

By comparing the electric resistance of the two solutions with that of a platinum wire taken as a standard, we find

* Each solution contained 60 grs. of sulphate in 300 grs. of water.

this relation equal to 0·0261 for the solution of sulphate of copper, and to 0·0320 for that of sulphate of zinc. But, from the experiments, the standard wire possesses a conductibility, such that for a current capable of giving ·061 cub. in. of gas per minute, the quantity of heat liberated would be 10·027. Therefore, if the law of proportionality of the heat liberated to the resistance is true for liquids, as for solids, we shall find the quantity equal, for sulphate of copper, to $10{\cdot}027 \times 0{\cdot}0261 = 0{\cdot}26$; for sulphate of zinc, to $10{\cdot}027 \times 0{\cdot}032 = 0{\cdot}32$. By experiments, we obtained 0·21 and 0·36.

The tolerably large differences, which are here manifested between the results of calculation and those of experiment, may be due to the chemical effects that necessarily occur at the surface of the electrodes, even when we have chosen the latter, so as to annul these effects as much as possible. Also, when engaged with liquids that undergo a real chemical alteration by the effect of decomposition, we must necessarily take account of these effects; for this decomposition is always brought about by absorbing the heat necessary for the new molecular equilibrium, a heat constantly less than that which is liberated by the effect of the resistance of the body to the passage of electricity, which is thus found diminished from the former, which we shall endeavour to estimate in the following Chapter.

It is not only in the liquid conductor interposed between the poles of the pile, but also in that in which the pairs are plunged, that we may verify the accuracy of the laws, that we have been stating. Mr. Joule has, in fact, proved that *the heat developed in a given time in each pair by voltaic action alone, is proportional to the resistance of conductibility of this pair, multiplied by the square of the intensity of the electric current.* From this law, combined with the preceding, the general principle is deduced that the heat, that is developed in any part of the circuit, is proportional to the square of the force of the current, multiplied by the resistance of this part of the circuit. If the law is exact for a part of the circuit, it must, according to the very just remark of M. Poggendorff, be applicable to the whole of the

circuit, including the pile. Hence the greater part of the differences that we have described (p. 240.), as existing between the voltaic pile and the electric battery, with regard to their calorific action. Mr. Joule has deduced also certain conclusions from the general law, which he has verified by experiment, of the relations that exist between the heat liberated by the entire circuit, and the chemical actions that occur in the circuit, both exteriorly to the pairs, and in the pairs themselves. The explanation of these researches cannot conveniently be given, until after having completed the study of the chemical effects of the current.

I must, however, before terminating this paragraph, make mention yet of an important principle, that I made known in 1843, and which M. Favre has recently confirmed by more direct experiments. This principle consists in the fact that the sum of the quantities of heat liberated by a given current, in the metal conductor, by which the poles of a pair are connected, and in the pair itself, is constant; only according to the thickness of the wire that serves as a conductor, it is sometimes one, and sometimes the other, of these two quantities that is the more considerable. A very simple method of making the experiment is to employ a pair of platinum and distilled zinc or cadmium with very pure and concentrated nitric acid for the liquid; and to unite the two metals by a platinum wire of greater or less thickness, which is entirely plunged into a capsule, similar to that in which the pair is contained, and filled with the same quantity of nitric acid. We observe carefully, with two very sensitive thermometers, the elevation of temperature of the acid in each of the two capsules; and we find that their sum, at the end of a given time, is always constant, the one being sometimes more, sometimes less considerable than the other. We may in like manner plunge the platinum wire by which the two metals of the pair are connected into the same liquid as the pair itself, and we see that for the same time, the elevation of temperature of this liquid is always the same, whatever be the thickness of the platinum wire. In both modes of operating, it is necessary to solder to the platinum and

and to the zinc or cadmium of the pair a rod of platinum of such thickness that it cannot become heated; by means of these two rods, the platinum wire of variable dimensions is placed in the circuit.

M. Favre employed a calorimeter similar to the one he had used in the beautiful experiments that he had made in conjunction with M. Silbermann, upon the heat liberated in different chemical actions, in order to confirm and to extend the principle that I have just stated. He also made use of a single zinc-platinum pair, and water acidulated with one-twentieth sulphuric acid; and he interposed successively in the circuit platinum wires of variable length and of different diameters. He always found that for 500 grs. of zinc dissolved, a total quantity of heat developed, equal to 18,137 units of heat, but distributed differently between the pairs and the platinum wire, according to the dimensions of this latter. But this quantity of heat is precisely that which is liberated by the mere solution of 500 grs. of zinc in acidulated water, by the effect of the different chemical actions that occur in it, whether the sulphate of zinc be formed by a transmission of electricity through a large wire, which offers no resistance to the current, or is formed directly without electricity transmitted; in this latter case, the quantity of heat was 18,444 instead of 18,137, which is evidently due merely to certain errors of experiment. M. Favre concludes from this that the heat developed by the resistance to the passage of electricity in the conductors of the pile, is a simple subtraction made from the total heat produced by the chemical actions that occur in the pair or pairs; and that it is rigorously complementary to that which remains confined there, so as to form a sum equal to the total heat corresponding only to the chemical reactions, independently of the whole electricity transmitted.

It would follow from M. Favre's law that, like as all chemical actions do not produce the same quantity of heat, so also the same quantity of dynamic electricity might also produce very different calorific effects, according to the nature of the chemical action which might have given rise to

it. M. Botto had already demonstrated this in some researches, in which he endeavoured to compare together the quantities of heat, liberated by the electricity derived from pairs of a different nature. We shall return to this subject, and to the different labours to which it has given rise, when we are engaged with the production of electricity by chemical actions. We shall content ourselves for the present with observing, that this very important element of the voltaic current, namely, the nature of the action that gives rise to it, or, which comes to the same thing, the nature of electro-motive force, plays, in the production of calorific effects, a part analogous to that of the density of electricity in the liberation of the heat brought about by electric discharges. This very just remark of Riess's, reveals to us that it is necessary, in like manner as we distinguish in discharges the density of the quantity, to distinguish in currents the *intensity* that would correspond to the density of the quantity: the study of the chemical effects of electricity will demonstrate to us this also.

Incandescence and Fusion of Metals by Dynamic Electricity; and the Molecular Effects with which they are attended.

We have confined ourselves in the two preceding paragraphs, to searching out the laws that regulate the simple heating of wires by dynamic electricity, without occupying ourselves with the changes, either permanent or transitory, in their appearance, which accompany this heating, when the electricity passes a certain degree of intensity. We have already made mention of these effects, both in the second paragraph of this Chapter, as well as in the fourth paragraph of the preceding. They consist essentially in incandescence, fusion, vaporization, as well as in inflexion, rupture, and other molecular modifications, which the wire suffers, by the passage of electric discharges, relatively more powerful than those which produce simple heating. The facts of this order are indeed essentially produced by discharges rather than by electric currents, being the result of a sudden and very in-

tense action, rather than of a moderate but continuous action; powerful currents, however, are in certain cases, able to manifest them. It is from Riess that we shall derive the greater portion of the details, that we shall give in the study upon which we are about to enter.

The first mechanical effect, that a thin wire experiences, when traversed by the discharge, consists of a sensible shock and of the formation of grey thick vapour, composed of metal particles detached from its surface. Sparks are at the same time manifested at the points of attachment of the wire with the conductors, intended for placing it in the arc, by which the circuit of the battery is closed; these sparks arise from the metal particles, a little larger than the former, which are torn off from the points of attachment, and which scintillate in becoming incandescent. The shaking is more sensible as the wire is more mobile; and, with regard to the sparks, they are more brilliant with platinum and palladium than with silver and brass; and there are none with copper. The scintillation even of the sparks depends at once on the tenacity of the metal and on its degree of oxidizability; also, there is none with silver, whilst with iron it is very powerful. The formation of the cloud of vapour is a phenomenon much more constant; but its intensity varies, not only from one wire to the other, but also in the same wire from the state of its surface. Thus a platinum wire, which has been well polished, carefully adjusted, and hermetically secured to its points of connection, requires a more powerful discharge than another similar wire, but which is not under the same conditions, in order to manifest the phenomena, that we have been pointing out. By gradually augmenting the force of the discharge, an alteration is observed in the physical state of the wire, which becomes persistent; it is an inflection that is at first manifested only as a diminution of polish in one point of the surface, and which ends by becoming more and more sensible, and by transforming itself into a very appreciable angle with sides some tenth of an inch or so in length. This angle is generally very obtuse, often

110°. It is equally manifested in wires of platinum, iron, and copper, even when they have considerable diameters. Its formation is more difficult, when the wire is strongly stretched; its place is then frequently supplied by a simple slight notch or by a tearing of the wire itself, which occurs where the inflexion would have been formed, if the wire had been able to yield. The undulating appearance, that is presented by the wires, when they have been raised several times in succession to a state of incandescence, by repeated discharges, is due to the formation of several of these angles, which modify each other in this manner.

To these inflexions we may evidently trace the shortening of wires, which have suffered a great number of discharges, and which Nairn and Van Marum had long ago pointed out, the former having succeeded, by means of fifteen powerful and successive discharges, in making an iron wire, that was 10·6 in. in length and $\frac{1}{10}$ in diameter, ·78 in. shorter; the latter having, by a single discharge, made an iron wire 25½ in. in length, ·31 in. shorter. Riess has actually shown that a platinum wire 6·8 in. in length, which had suffered a shortening of ·46 in. by the effect of discharges, returned, within about ·07 in. of its primitive length, by being simply drawn between the fingers; he satisfied himself that this apparent shortening is always due to the inflexions which, in certain cases, escape a superficial observation.

M. E. Becquerel had equally observed that, whether in air or *in vacuo*, wires of platinum and of silver, of a very small diameter, shorten and become undulated, under the action of one or of several discharges; and that this effect increases with the number of the discharges.

The incandescence of wires is subject to the same laws as the simple heating: Riess has demonstrated this by placing in the closing arc an electric thermometer, furnished with a wire, sufficiently strong not to undergo mechanical alteration, but to suffer a simple heating by the effect of the discharge, whose intensity it serves to measure. Thus, in seeking to determine the quantity of electricity and the number of jars, necessary for bringing a platinum wire of

a given dimension to a state of incandescence visible by daylight, it is found that in order that the heating, indicated by the electric thermometer, and the incandescence shall remain the same, it is necessary that the product of the quantity of electricity by its density shall be constant. In the experiments made by Riess, this product $\frac{q^2}{s}$ was at a mean 31, q being the quantity of electricity, and $\frac{q}{s}$ its density; it follows from this that, knowing this product 31, we may determine, for any number s of jars, the quantity of electricity q, necessary to render the same platinum wire incandescent. In fact, it is necessary to have $\frac{q^2}{s} = 31$ or $q = \sqrt{31s}$.

The following is a Table of the comparative results of calculation and observation, as Riess obtained them: —

Number of jars - -	2	3	4	5	7
Calculated value of quantity	7·9	9·6	11	12·4	14·7
Observed „ „	8	10	11	12	14

It is remarkable that the observed values agree so well with the calculated values, in the appreciation of a phenomenon, in which the sensibility of the eye plays so important a part.

The force of the discharge, necessary for the production of incandescence is, as for simple heating, independent of the length of the wire, and proportional to the fourth power of its radius. In order to demonstrate the accuracy of the former law, we take first a platinum wire 1·37 in. in length, and find that, in order to render it incandescent, a discharge is required determining in the electric thermometer a heating equal to 8, produced itself by 4 jars, with a quantity of electricity $q = 12$, or by 7 jars with $q = 15$, which comes to the same thing, according to the preceding law. With a wire five times longer, namely 6·85 in., we require, it is true, with 4 jars, a quantity of electricity $q = 22$, but producing on the thermometer the same heating, 8, which proves that the force of the discharge has remained the same.

The second law results from experiments made with five wires of different diameters, placed successively with the electric thermometer in the same closing arc. By calculating, according to the law, what ought to be the force of the discharge, or, which comes to the same thing, the temperature indicated by the electric thermometer, in order to produce the incandescence of each of the five wires, and by comparing the result of calculation with that of observation, the following Table is found:—

Radius of the Wire.	Temperature of the Electric Thermometer.	
	Observed.	Calculated.
0·00157 in.	1·2	1·3
0·00184 „	2·7	2·3
0·00231 „	5·8	5·4
0·00255 „	8.1	8·0
0·00353 „	31·0	32·4

When the object is to compare the electric charges necessary for producing the incandescence of the divers metals, the experiment is much more difficult; because the colour of the metal, its greater or less facility of oxidising, render the observation uncertain. However, Riess succeeded, by the same method as the above, in determining for wires of the same diameter, but of different natures, the force of discharge necessary, in order to render them incandescent. The following are the results, that he obtained with the metals of commerce, and consequently those, whose chemical purity cannot be guaranteed.

Iron	0·816
German silver	0·950
Platinum	1·000
Palladium	1·070
Brass	2·590
Silver	4·980
Copper	5·950

We plainly see that, in order to produce the same incandescence in each wire, the force of the discharge must be

greater, in proportion as the resistance to the passage of electricity is less; a result similar to what we had obtained for heating, and which had for a long time been proved, as we have remarked, by a great number of philosophers, both for the incandescence produced by discharges, and for that, which is brought about by the electric current. But, independently of this cause, the specific heat of the metal, and its density, must exert an influence, which might be accurately estimated, if we could be certain that incandescence commenced for the different metals at the same temperature. In this case, indeed, we ought to obtain the same quotient by dividing the product, formed of the force of the discharge necessary for each metal, in order to become incandescent, multiplied by its electric resistance, by the product of its specific heat and its density; and this is what does not take place. This is due to other circumstances, exercising an influence over the incandescence, such, especially as the greater or less facility, with which the metals absorb the oxygen of the air. We cannot therefore attach a great theoretical importance to the results included in the above Table.

It remains, therefore, for us to study the phenomena of tearing, of fusion, and of pulverisation, which succeed to an incandescence, brought about by a charge too powerful for the wire to be able to remain intact or to suffer merely simple inflexions; these are effects partly calorific and partly mechanical, which it is important to analyse well, in order to form a correct idea of this order of phenomena.

When we gradually increase the quantity of electricity, necessary for the production of the simple incandescence of the wire, we at first obtain a very vivid incandescence, then the wire becomes very white, and finally it breaks into two or into several fragments; the aspect of these fragments shows that it is rather a tearing than a fusion that is brought about. The difference between the intensity of the discharge, which simply produces incandescence, and that of the discharge that produces the tearing, varies with the nature of the metals; it is great with platinum and palladium, smaller

with copper, silver, and iron, and very feeble with brass. It is much less for a metal, that has already suffered the discharge, than for that, which suffers it for the first time. In order to examine the state of the fragments, we must place the wire in a glass tube; we sometimes perceive the fragments to become soldered one to the other; but they present no trace of fusion at their extremities, which are pointed, as if the wire had been broken, by a force that would have drawn it in the direction of its length. In order to avoid these superficial fusions, we must employ a more powerful discharge. Thus in a bell-glass $7\frac{1}{2}$ in. in height, and $5\frac{3}{4}$ in. in width, a battery of five jars rendered a platinum wire 1·68 in. in length, and 0·00279 in. in radius, incandescent with a quantity of electricity equal to 12; and broke it into several fragments with a quantity equal to 17; whilst a copper wire, under the same conditions, required 23 of electricity, in order to become incandescent, and 27 in order to be torn. The metals, that enter easily into fusion, such as wires of tin and of cadmium, are torn without passing through incandescence.

If we exceed the force of discharge, that tears the wire, we succeed in melting it, at the same time breaking it into a large number of fragments. Thus, a platinum wire similar to that, which had been torn by the quantity of electricity equal to 17, was broken and partially melted, with a quantity equal to 20. Wires of silver and of tin experience the same effect. But, in order to obtain a complete fusion, more powerful discharges are necessary. The wire is then reduced into perfectly round small balls; this is easily observed with wires of platinum and silver; for a copper wire 1·41 in. in length, and 0·0022 in. in radius, a battery of six jars raises it to incandescence with a quantity of electricity equal to 25; and, with a quantity equal to 30 only, it divides it into an infinite number of small and scarcely perceptible balls. The difference between the quantities of electricity is very small; this is probably due to the circumstance that, with easily oxidisable metals, the temperature is increased by the presence of the oxygen of the air; it thus adds a che-

mical heating to the electric heating. This effect is especially sensible with iron, which often melts under the influence of discharges, that could only have produced a moderate amount of heating. Incandescence in this case does not cease immediately after the discharge has taken place, as commonly happens, but the wire attains to white incandescence, and melts into drops, which spurt in scintillating.

Fusion is therefore a very complex phenomenon; so that it is impossible to establish for each kind of metal the force of discharge, necessary for melting it; the more so because, as Van Marum has observed, all the electricity of the battery is not employed in bringing about the fusion, and that there remains a residue in the battery itself, which is sometimes very considerable. This effect, which Riess has studied with care, is due to the electricity producing the disorganisation of the wire, in an instant too short to allow time for its passage entire. It is very curious that the residual after the reduction of a wire into fragments, is 0·23 of the whole of the electricity, that was in the battery; whilst it is only 0·15, namely less considerable, after the simple explosive discharge through air.

We have seen that the first effect of the discharge upon a wire is the formation of a small cloud of vapours, which proceed from the particles detached from the surface. With a sufficiently powerful discharge, we are able to reduce even the whole mass of the wire into a similar vapour. A platinum wire, subjected to the discharge of five jars, became incandescent with $q = 13$, melted into small globules with $q = 17$, and disappeared with a brilliant light, leaving the tube, within which it was enclosed, covered with a grey film, that might easily be removed. In the open air, the vapour collected upon a plate of copper presented grey and blackish spots, which appeared to be formed of metal fragments, of various forms and sizes, and which presented no traces of fusion. The pulverisation, therefore, is very distinct from fusion; and what proves this is that tin, which requires for its melting a less charge than cadmium, requires a greater, in order to its becoming pulverised. In general, in the open air, the

pulverised metal is at the same time oxidised: we may collect very visible traces of this, by placing upon a sheet of white paper, the wire that is to be pulverised, and, if we desire to obtain traces of the metal itself, and not of its oxide, we have merely to pulverise it in a bell-glass, where there is nitrogen or very rarefied air. We must take care in these experiments to stretch the wires well, placing them between two sheets of paper.

To sum up, if we follow the series of effects, that are produced by discharges of increasing intensity, we find that the wire begins by heating, that it suffers a shaking, then inflexions, that it becomes incandescent, that it is torn from the pincers in which it was fixed, that it is broken into fragments, melted, and finally pulverised. The calorific and mechanical effect, are thus found mingled together, in a manner not only to succeed each other alternately, but also to be found simultaneously in several cases. Thus the incandescence of a wire never occurs, without there being at the same time inflexions, and it is rare that a fusion is obtained, without there being at the same time a rupture of the wire into fragments. The pulverisation, likewise, is always attended by a great elevation of temperature, as is proved by the oxidisation of the metallic powders. This association of the two species of effects leads to the presumption that they are connected by a mutual dependence. And, indeed, it is easy to prove that incandescence and fusion are not a simple effect of the liberation of heat by the discharge, following the laws established by experiment; for this heat, the intensity of which may be calculated by knowing the force of the discharge, would be far from sufficient to produce incandescence and fusion. There is, therefore, in the production of these two phenomena, a direct effect of electricity, independently of the indirect action which it exercises in the production of heat. Riess estimates that this double mode of action is due to the transmission of the charge being brought about, in a manner altogether different, for the production of the heating of the wire, from that in which it takes place in order to cause mechanical effects, in the

number of which must be placed incandescence and fusion. We shall return to the mechanism itself of the discharge, when we shall have studied its calorific and luminous effects, in its passage through imperfect conductors.*

This mechanism appears, in certain points, to differ from that of the voltaic current, which would only possess the mode of transmission, proper for the development of heat; for, with this current, the phenomena of incandescence and fusion, appear to be nothing more than a simple consequence of an increase of heating; and no such mechanical effects as rupture and pulverisation are observed. However, we may notice in wires, that have suffered incandescence, an alteration at their surface of the same kind as that which we have called inflexion. This alteration is even more profound; for wires, that have been rendered incandescent by the passage of a powerful voltaic current, become more brittle, and seem to undergo a modification in their molecular structure. I have often observed this with platinum wire, a proof that this is not an effect of oxidisation.

There exist, also, in the calorific and luminous effects, produced by piles of high tension through imperfect conductors, particular phenomena, which equally denote a kind of mechanical action, exercised by currents, analogous, up to a certain point, to that of discharges. Finally, for the effects of the incandescence of wires by the current, we should have to prosecute a study, analogous to that, which was made by Riess for discharges; and perhaps we might find more varied results and more detailed laws than those which we have stated wherein we treated upon this subject.

Calorific and luminous Effects of Discharges through imperfect Conductors.

After having studied the luminous, and principally calorific effects of dynamic electricity, when it is transmitted through good conductors, it remains for us to turn our

* Grove has also observed a remarkable shortening in leaden wires after having once conducted the electric current.

attention to the same effects, when the conductor is imperfect. This imperfect conductor may be solid, liquid, or gaseous; but it is more particularly in the two latter cases, and especially in the last, that the phenomenon, at the same time calorific and luminous, that accompanies either the electric discharge, or the passage of a current, is manifested. We shall, in the study of the phenomenon, distinguish the case, in which it is produced by discharge,—the one which is now about to engage our attention,—and the case, in which it is produced by current, to which we shall consecrate the following paragraph.

In general, the luminous appearance, that accompanies the electric discharge through an imperfect conductor, we call *the electric spark*. This appearance is presented under very various forms, according to the physical state, and the nature, either of the medium, in which it is manifested, or of the good conductors, commonly metallic, between which the discharge is brought about. In the common air, and with conductors in the form of balls and made of brass, the spark has the form of a line of a white colour, with a slight reddish tinge at its two extremities. If the discharge is powerful, the spark is long, and formed of broken and slightly curved lines. With good electrical machines, and without the assistance of Leyden jars, we may obtain sparks of a foot in length, very white and very brilliant, in which the zig-zag form is very decided. This form is evidently due to a condensation of the air, which being brought about in the direction of the discharge, obliges it to deviate laterally, but in no way modifies its point of departure and its point of arrival.

We may increase the luminous effect of the spark, by means of spangled tubes, which are glass tubes, upon which are glued in a spiral form little lozenges of tinfoil, the points of which are very near to each other. At their extremities, are fixed balls of metal, which are in communication with the lozenges next to them; one of the balls is held in the hand; and, on drawing sparks from an electrical machine with the other, sparks are seen to dart at the

same time between all the points; but the light ceases to be so vivid, and it acquires a reddish tint, which it owes in part to the form, and in part to the nature, of the little lozenges.

Before investigating the properties of the spark, and in particular its luminous properties, we must analyse the circumstances, that exert an influence over its form, and in general over its appearance. These circumstances are chiefly the intensity of the discharge, which gives rise to it, then the form of the conductors between which it escapes, and the nature of the medium, that it traverses. The nature of the conductors, between which it moves, may modify its colour, but not its form.

In atmospheric air, under the ordinary pressure, the electric spark often acquires the form of a brush. This form is presented, when the electricity of a machine escapes by an angular part of its conductor (*fig.* 203), or escapes from a conductor, surrounded by a piece of cloth or silk, covered with metallic powder. At its point of escape, the spark presents only a line; but it very quickly ramifies into a bundle of small sparkling filaments. With a good electrical machine, it is sufficient to fix upon its conductor a long metal rod, a quarter of an inch or so in diameter, terminated by a little ball some $\frac{3}{4}$ in. in diameter, in order to see a beautiful brush dart from the ball (*fig.* 204.), when the machine is put into action. If a smaller ball is employed, still having the same electrical machine, the brush is more feeble, and the sound, that accompanies it, although less decided, is more continuous. With smaller balls, or with conductors, terminated in fine points, the brushes diminish still more, and the sound becomes scarcely perceptible. When the sound ceases, the light changes in appearance, and becomes continuous, like a glow, instead of appearing like a succession of small points of very vivid light.

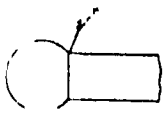

Fig. 203.

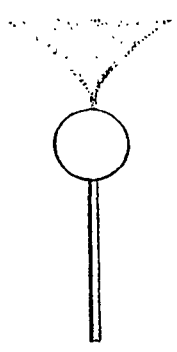

Fig. 204.

The brush seems, therefore, according to Faraday, who has made a very special study of it, to be the result of a succession of little discharges between the conductor, and the successive particles of air, polarised by induction. This would explain the production of the sound. Wheatstone, indeed, showed, by means of his turning mirror *, that the brush, although it seems to be continuous, consists of successive and intermittent discharges. Faraday justly regarded this phenomenon as the result of the discharge, that occurs through air, between the extremity of the electrised conductor and a neighbouring body, in the absence of the walls of the apartment, electrised by induction. The interposed air is polarised, as every other di-electric body would be; and as the filaments of air converge toward the point of the conductor, from which the brush sets out, it is in the neighbourhood of this point that their polarity is the strongest. So that, when this polarity becomes sufficiently powerful for discharge to take place, the filaments of air are luminous only in their part that is nearest to the point, from which the brush originates, where they are most concentrated. Further on, there is indeed a succession of discharges, but the filaments being more divergent, the intensity is more feeble; there are only obscure discharges without light. The inductive influence of neighbouring bodies is so necessary for the production of the phenomenon, that, when the electrical machine is feeble, we have merely, in order to give rise to the brush, to bring the hand or a conducting body near, in order to bring it about, and to give it a form and a direction, which vary with the

* We have seen that Wheatstone succeeded, by means of the reflection produced by a mirror, that turns around an axis with very great rapidity, in seizing the slightest differences of time, between luminous appearances, that seem to be simultaneous (*vide* p. 182.). By the same method, he assured himself of the instantaneity of the light of the spark, the image of which is not changed by the movement of the mirror, whilst that of the brush is elongated in the direction of the movement; which proves that the discharges of which it is constituted, endure for a certain time, appreciable by the movement of the mirror. At the same time, the successive sparks, that constitute the bundle, which is itself placed on the prolongation of the axis of the turning mirror, being each reflected by a different part of the mirror, present themselves as if arranged at regular distances in a circle, a proof of their discontinuity.

position of the conductor (*figs.* 205, 206, 207.), so as to demonstrate that it is really the result of the discharge, that is brought about between the two conductors.

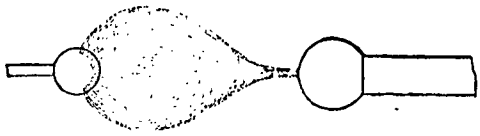

Fig. 205.

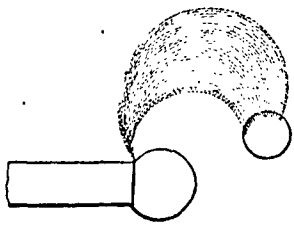

Fig. 206.

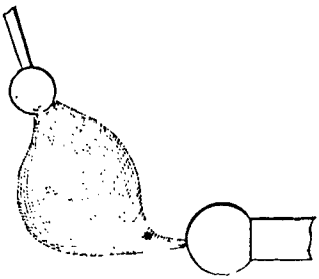

Fig. 207.

In the preceding experiments, the electricity of the conductor, whence the brush originated, was constantly positive; if the conductor, terminated in a point, is charged with negative electricity, then we see appearing upon it, a simple luminous point, or rather, as it were, a little luminous star. But we may nevertheless obtain a brush with negative electricity, by using, instead of a point, a conducting rod terminated by a rounded form. Only the brush is much shorter (*fig.* 208.), and the succession of discharges, of which it is composed, is much more rapid (seven or eight times) than in the case of positive electricity, as is indicated by the sound that accompanies it.

Fig. 208.

Another very remarkable difference may be observed, when the rounded end of a wire, that is held in the hand, is brought near to the negative brush: this extremity becomes positive by induction, and shows, even at the distance of 7 or 8 in., a brilliant glow, without any change having yet occurred to the negative brush; but at a less distance, the sound of the negative brush becomes more acute, which indicates a more rapid succession of the small discharges, of which it is composed;

at a still less distance, a positive brush shows itself at the extremity of the induced conductor, but, at the same time, the negative is contracted; and, both of them are seen simultaneously with a very different appearance (*fig.* 209.). By employing as an induced conductor a rather fine wire, we are able to obtain, at a certain distance, two brushes, one positive, the other negative, perfectly similar and giving sounds in unison.

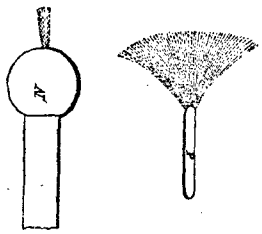

Fig. 209.

To conclude, the negative conductor comports itself like a positive conductor, the electricity of which has less tension, which is in accordance with the remark that we have already made in the First Chapter of this Fourth Part *, that negative electricity discharges itself in air, at a lower tension than that which is necessary for positive. Faraday had proved this fact, which had already been pointed out by Belli and several other philosophers, by causing, as we have said †, the discharges to occur between balls of different dimensions, and by studying the formation of the brushes on the inducing and the induced balls, both positive and negative. We shall see further on, that this phenomenon is due to a more general difference, which exists between the properties of positive electricity and those of negative, when they both, in order to neutralise each other, come out from a conductor, in which they are accumulated. But we have first to study the effect of the nature of the surrounding medium upon the form and the appearance of the spark.

When the spark is produced in a space, wherein the air is rarefied, it is seen to subdivide, to become feeble, and to acquire a reddish tinge. In a tube two or three yards long, and in which a vacuum has been made, or at least in which the air has been rarefied as much as possible, the spark produces a magnificent reddish violet glow, which fills it entirely, and which seems to circulate interiorly in the form of a helix, which is probably due to the conducting influence of the film of moisture adhering to the glass. The

* Vol. II. p. 166. † Vol. II. p. 166.

spark is transmitted through the tube by means of two metal ferules, placed at is extremities, and terminated exteriorly, one by a ball, that communicates with the machine, whence the spark is derived, and the other by a stop-cock, which allows of vacuums being made in the tube, and which is made to communicate with the ground. We may also observe the luminous effects of electricity, by means of the electric egg, which is a glass vessel of an ovoid form, at one of the extremities of which is adapted a tube, with a stop-cock, and at the other a rod with a knob, passing into a collar of leathers (*fig.* 210.). The air is rarefied more or less, by

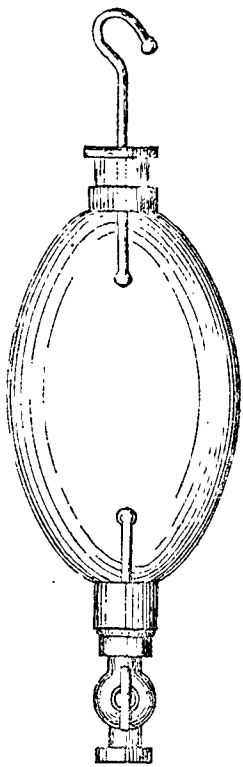

Fig. 210.

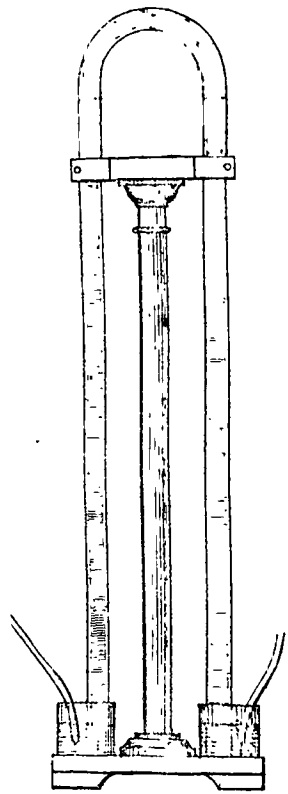

Fig. 211.

screwing the tube on the plate of an air-pump; in proportion as the air is rarefied, the knob of the movable rod may be

withdrawn further from that of the fixed rod, adjusted by the stop-cock; and the spark as it becomes longer, loses its vivacity, acquires a reddish violet colour, and is subdivided into a multitude of elliptic jets. This is a true brush, of the kind given in *fig.* 205., very long, and composed of ramifications very large and distant from each other, sometimes as much as half an inch or more.

However, when the discharge is very strong, such as results from a powerful battery, we obtain *in vacuo*, a light as vivid and as brilliant as in air. If the light is generally feeble and diffused *in vacuo*, it is due to the discharge being enabled to take place under a far less amount of tension than in air, which enables the electrical machine, with which one of the knobs of the electric egg is put in communication, to give off its electricity in proportion as it is developed: it is no longer the same, if we accumulate the electricity by means of a battery, so as to transmit the whole of it at once.

Finally, we may obtain the spark in the barometric vacuum, by means of a tube bent into the form of a siphon, and forming a double barometer (*fig.* 211.): the electric spark is made to pass from one cup to the other, by obliging it thus to traverse the two columns of mercury, and the empty space by which they are separated. The spark fills this space with a diffused violet light; it requires a very feeble electric tension, in order that the phenomenon may take place.

Davy made a special study of the electric light *in vacuo*, or rather in spaces filled with vapours of different kinds. He operated by means of a bent tube, having one branch closed and longer than the other (*fig.* 212.). A platinum wire was cemented in the extremity of the closed branch, so that one part was outside and the other within. The closed branch was filled with mercury, very much purified and freed of air and of aqueous vapours; vacuum was then made in the open branch, which was furnished with a stop-cock at its extremity. An empty

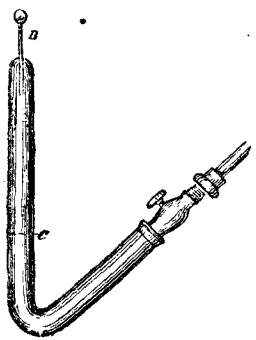

Fig. 212.

space, of greater or less extent, is thus formed at the top of the closed branch. The spark of a machine, or, still better, that of a Leyden jar, traversed this space, and produced in it a luminous effect; but this effect was much increased, by gradually heating the mercury to a state of ebullition; the light was then of a green colour, the brilliancy of which was most striking. In proportion as the temperature was lowered, the colour lost its vivacity; and at 29° F. the light was so feeble that it could only be perceived in the most profound darkness. A small quantity of air, introduced into the mercurial vacuum caused the colours to change from green to sea-green, then to blue and to purple. By substituting the fusible alloy of bismuth and tin, in place of the mercury, a yellow and very pale light was obtained; with pure olive oil and liquid chloride of antimony, the boiling temperature of which was not far from that of mercury, Davy obtained a light rather more brilliant than that which arose from the electricity, liberated in the mercurial vacuum; it was of a red colour tending to purple with oil, and of a pure white with chloride of antimony. We may add that, when the temperature is very low, it requires a very strong discharge, in order that it may be transmitted through the barometric vacuum. These experiments of Davy's show the important part played in the production of the electric light, by the bodies between which the discharges pass, and the particles, that are very probably detached from them, by this discharge itself.

The spark changes also in appearance if, instead of transmitting it through the air or through an empty space, it is made to pass into different gaseous media. In nitrogen, the sparks are more brilliant than in air, and are especially accompanied by a very remarkable sound; in oxygen, they are whiter than in nitrogen or in air, but not so brilliant; in hydrogen, their colour is crimson; in dry hydrochloric gas, the spark is always white; and these differences are doubtless due to the greater or less facility, with which the different gases allow of the passage of the discharge, as we have seen in the preceding chapter.* Faraday, to whom we are indebted for these

* Vol. II. p. 161.

various observations, has also remarked that the electric spark may be equally obtained in various liquids, such as essence of turpentine, olive oil, resin, melted glass, and in water itself, &c.

The brush also, like the spark, varies in appearance, with the different media, in which it is produced. We have seen, by the experiment of the electric egg, that, in rarefied air, it is extremely brilliant, and is composed of very elongated branches. It is the same in all the gases; as soon as they are rarefied, the spark is gradually converted into a brush, which becomes more and more considerable and ramified in a distinct manner, until, at a certain degree of rarefaction, the brushes, that arise from the positive and negative conductors, unite, so as to form together a continuous luminous jet. The phenomenon varies with the size of the vessel, the degree of rarefaction, and the force of the spark, that is given by the machine. If we now examine the appearance of the brushes in the different gases, we find that in oxygen they are very compressed, and in general much more feeble than in air. The reverse is the case in nitrogen; this gas is the one in which they are most luminous, and in rarified nitrogen, in particular, they are magnificent. In hydrogen, they are much less brilliant than in nitrogen, but more than in oxygen; their colour is of a greenish grey. In oxide of carbon and in carbonic acid gas, they are difficult of production; they are short and their light is feeble. In hydrochloric acid gas, the brush is still more difficult to be obtained under ordinary pressures. By gradually increasing the distance between the two rounded extremities of the conductors, between which the discharge occurs in this gas, the sparks cease, and at a distance of $\frac{5}{4}$ in. between these extremities, the discharge occurs without spark and noise; it is probable that in this case an electrolytic discharge is brought about, namely an electro-chemical decomposition of the gas; which we shall see in the following Chapter.

The brush is not only observed in air and in the gases, but also in more dense media. Faraday succeeded in producing it in essence of turpentine, by plunging into it the

end of a wire, placed in a glass tube, the liquid itself being in a metal vessel. The brush was very small, and was obtained with difficulty; its ramifications were not numerous, and diverged much from each other; and a very dark chamber was necessary for observing it, so feeble were its ramifications. A very remarkable thing is that, whilst the medium, in which it is propagated, may singularly modify the brush, the nature of the body, from which it originates, does not seem to exercise over it any other influence than that which arises from the greater or less degree, with which this body, according to its conductibility, facilitates the discharge of the machine. It is the same with the negative brush; but the latter, like the positive, suffers very decided effects on the part of the medium, in which it is produced. Thus the rarefaction of the air facilitates its development still more than it facilitates that of the positive. The superiority of the positive brush over the negative, which is already very considerable in air, is still greater in nitrogen. In hydrogen, on the contrary, the positive brush loses a portion of its superiority, whilst the negative is but little or not at all affected. Finally, in oxygen, carbonic acid, and hydrochloric acid, all difference disappears between the two brushes, so that it is a very difficult matter to distinguish them from each other.

There exists, also, besides the spark and the brush, a peculiar form, under which the light produced by the discharge is manifested, and which we will designate under the name of *glow*. It is manifested when we diminish the surface of the ball and of the rod, that are in communication with the machine; the brushes then disappear, and their place is supplied by a continuous phosphorescent glow, which covers the entire end of the wire. This luminous form appears to arise from the rapidity with which the discharge is renewed; for, by increasing the force of the machine and the rarefaction of the air, we favour its production.

The glow is obtained with much more difficulty with negative, than with positive electricity; in order to produce it, it is necessary to rarefy the air, and, by adjusting the two balls to a suitable distance, we are able to obtain upon the

negative ball a glow, which covers it entirely, and equally well when it is inducing as when induced. We perceive the two balls, and a tolerably long portion of the two rods by which they are carried, covered with this electric light.

The glow presents itself equally in all the gases. Faraday thought he had obtained it in essence of turpentine, but very feeble and scarcely visible; it is accompanied in the air by a puff of air coming in general from the luminous part, but sometimes also directed towards it. Thus it is probably due to a very rapid charge or discharge of the air, by which the conductor is surrounded, and which remains adhering to it, even in the most perfect vacuum. This air, by virtue of the electricity that it acquires and loses, assumes a regular movement, and gives rise to a continuous glow, without there being any appearance of agitation. In proof of this explanation, Faraday quotes an experiment, in which he succeeded in converting a brush into a simple glow, by facilitating the formation of a current of air at the extremity of the conductor, when the brush was produced. In like manner, by interfering with the current of air, a simple glow may be changed into a brush. It is easy to follow the transition from the glow to the brush, and from the brush to the spark. Every thing that tends to facilitate the charge of the air by the electrised conductor, and to preserve to this conductor its same tension, notwithstanding the discharge, contributes to produce the glow; whilst circumstances that prevent the air or other gases from becoming charged with electricity, and which favour the accumulation of electricity upon the conductor, determine intermittent discharges, under the form of brushes and sparks. Thus the condensation of the air, the neighbourhood of the hand or of any conducting surface, acting by induction, the gradual approximation of a ball, intended to receive the discharge, provoke the cessation of the glow, and its change into a brush or a spark. In conclusion, the continuity of the discharge produces the glow, the discontinuity produces the brush, and the spark when it becomes more decided.

It frequently happens that, in its passage through a

transparent medium, the electric discharge is not luminous throughout: this is what Faraday called the *dark discharge*. Thus, if we separate from each other two metal rods, between the extremities of which the discharge is passing in rarefied air, a continuous glow is perceived upon the end of the negative rod, whilst the positive extremity remains altogether dark. In proportion as the distance increases, a train of purple or of white light appears at the extremity of the positive rod, and advances directly on the negative rod; it elongates itself, but yet without ever joining the negative glow, so that there is always between them a small obscure space (*fig.* 213.). This space, which is about $\frac{1}{10}$ in.

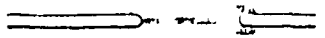

Fig. 213.

or less in width, remains invariable in its extent, and in its position, with regard to the negative point; the negative glow no longer changes whilst the purple light of the positive point is seen to lengthen or to shorten, in proportion as the distance of the two points is made to vary. An effect of the same kind is presented in all the gases; only according to the nature of the gases, the ends of the two rods must be withdrawn to a greater or less distance from each, in order to obtain the dark discharge. In general, the position of the dark space is constant; and we may satisfy ourselves, by carefully examining the phenomenon, that this space exists between the positive and the negative glow, even when it is a difficult matter to observe it, on account of the concave form of the former glow, and the convex form of the latter. This experiment shows that the discharge may be transmitted through a gas, without necessarily rendering it luminous.

Faraday, who has much studied this question, considers that the dark discharge occurs at a very feeble tension; and that, after it has commenced, the light is the consequence of the greater quantity of electricity that is forced along

the same route, finding in this direction a more easy passage.

We may obtain the discharge under the form of the glow, and the dark discharge, in a very decided manner, by the sparks, that are produced by induction apparatus; especially by Rumkorff's.* We have merely to connect the two ends of the induced wire respectively with the balls of the apparatus, called the electric egg (*fig.* 210.) in order to obtain, on rarefying the air, glows in all their beauty around the two balls, with certain differences, however, at the negative and at the positive ball. M. Rumkorff, who has repeated with variations the experiments of MM. Masson and Breguet, has remarked that the light which surrounds the negative ball and rod, is violet; and that which is around the positive ball is a fiery red, and that it extends toward the negative ball. There dart also from the two balls certain sparks more white and distinct from the glows which probably arise, as we shall see, from the metallic particles, detached from the balls. Mr. Gassiot has observed that, when the vacuum is well made, half of the negative ball is surrounded by a brilliant blue flame; whilst there escapes from the positive ball a line of brilliant red light; but there is between the red line and the blue flame a space completely dark.

M. Quet, on his part, has discovered that the double light, which emanates from the two balls, is composed of a succession of brilliant strata, entirely separated from each other by dark strata; and that it is as it were stratified. In order fairly to observe this phenomenon of stratification, we merely require the presence, in the vacuum made in the electric egg, of a very small quantity of alcohol†, essence of turpentine, sulphuret of carbon, or oil of naphtha. By causing the induction current of Rumkorff's machine to pass between the balls, we observe a multitude of brilliant strata, separated by dark strata, forming as it were a

* Vol. I. p. 389. *fig.* 150.

† M. Rumkorff was the first to obtain this phenomenon of stratification, by placing for a few moments over an open jar filled with alcohol, the opening of the electric egg, before making the vacuum in it.

pile of electric light between the two poles. The stratification is more decided in the red light of the positive pole, than in the violet of the negative; but the number of alternately dark and brilliant strata is less considerable. It is moreover easy to prove that the light of the positive pole is separated from that of the negative by a dark stratum, which may be rendered more or less thick, according to the perfection of the vacuum, and the nature of the vapour that it contains.

The light in these experiments does not possess a continuous duration; it consists, indeed, in a series of discharges that succeed each other with rapidity. This gives rise to an oscillating movement of the luminous strata, which renders the observations a little difficult. In order to avoid this inconvenience, M. Quet manipulated with his hand the little magnetic hammer of Rumkorff's apparatus, and at each movement an emission of vivid light is obtained, but which endures only for an instant; the entire succession of strata, alternately brilliant and dark, are thus marked out in a very distinct form; by renewing this manipulation at pleasure, the details of the phenomenon may be easily studied.

The colour of the light varies with the nature of the vapours that are contained in the vacuum; with that of essence of turpentine we obtain, at the positive pole, a beautiful white and phosphorescent light, the stratification of which occurs by flat strata, but of unequal thicknesses; with the vapour of fluoride of silicium, a yellow light is obtained at the negative pole. If the two balls are brought very near to each other, one or other of the two lights is at last made to disappear; this depends upon the nature of the vacuum; in the vacuum where there remains only very rarefied air, it is the red light of the positive pole that disappears completely; the violet of the negative remains alone.

This last phenomenon is precisely the same as that described by Faraday under the name of the dark discharge. We have indeed just seen that, when the spark is produced in rarefied air, and between two conductors very near together,

the negative conductor alone is surrounded by a blue glow and the positive conductor remains dark, whilst in the atmosphere, the two conductors appear equally luminous. Electricity is therefore discharged from the positive conductor, without producing light, as well with induction currents as with the electricity of an ordinary machine.

Previously, however, to M. Quet, M. Neef, on observing with a microscope the passage of an induction current between a platinum point and an oscillating plate of the same metal, by means of an apparatus similar to the one we have already described*, had recognised that the negative electrode alone was luminous. He thought he might conclude from this observation that the electric spark engenders, at the negative electrode, light without heat, and at the positive, heat without light. We shall return hereafter to the labours of M. Neef; we will confine ourselves for the present to remarking that it is still the same phenomenon of the dark discharge, with this very important difference alone, that it occurs in air instead of in vacuo. M. Riess has succeeded in demonstrating that the difference is more apparent than real; because, when the sparks succeed each other very rapidly, in a very contracted space, the air is promptly rarefied between the electrodes. Indeed, by varying at pleasure the distance by which the point and plate of platinum are separated, Riess remarked that, when the distance is rather great, the spark presents no particular appearance; there is a continuous luminous arc at each spark between the plate and the point; by diminishing the distance, we obtain sparks more and more numerous and nearer together; finally, at a shorter distance still, the spark loses all its brilliancy, and at the same time a bright blue light is shown at the surface of the negative electrode alone. We perceive within this blue light, on observing it by means of the microscope, a certain number of very brilliant white points; which appear to be particles of incandescent platinum, detached by the discharge; and this is confirmed by the state of roughness, presented by

* Vol. I. p. 387. *fig.* 149.

the surface of the platinum plate, after having been used for some time in these experiments. We may add that Mr. Gassiot observed, when employing as electrodes two platinum wires $\frac{1}{10}$ in. apart, that the negative wire becomes fiery red, whilst the positive remains cold; in this case, the discharge is very rapid and continuous. This effect would be the reverse of that pointed out by M. Neef, and contrary to what occurs with ordinary currents. These oppositions may be due to the difficulty there is in distinguishing fairly, in induction currents, the positive from the negative pole. Nor must we lose sight of the fact that electro-chemical effects occur, arising from the decomposition of the gases, or rarefied vapours, that are traversed by the discharges, which may contribute to the appearances presented by the light. We shall explain these in the following Chapter.

After having studied the electric spark, the manner in which it arises, and the different forms that it assumes, it would remain for us to examine its various properties; but we shall return to this examination in the eighth paragraph, in order to make it comparatively with that of the voltaic arc; and thus to be able, when appreciating the differences that characterise these two forms of the same phenomenon, to trace them to their common cause. We shall confine ourselves here to saying a few words on the calorific effects of the spark, of which we have already had examples, in the inflammation of combustible bodies, and especially in the experiment of Volta's pistol. Chemistry derives great advantage from this property of the electric spark, in order to bring about the combination of gaseous mixtures. They are introduced into a glass tube, with very strong sides, and graduated: this tube, closed at one end, rests by its open end in a water-bath, filled with water, or, still better, with mercury. Two metal points, generally platinum, penetrate interiorly into the upper part of the tube, into the sides of which they are hermetically sealed, so as to allow between them an interval of at the most not more than $\frac{1}{10}$ in.; in order to cause the spark to dart through the gaseous mixture, the metal points are put in communication, by their outer extremity, with the coatings of a Leyden jar;

the fire is thus conveyed into the interior of the tube, without there being any need to heat it exteriorly. The same effect may be produced by the incandescence of a fine platinum wire, by means of a current: a proof that the combination is altogether due to the heat liberated, as well in the spark as in the wire; and that it is not an immediate effect of electricity. Moreover, we shall study, more in detail, the chemical effects of the spark in the following Chapter.

We have further proofs of the heat of the spark, from the traces it leaves upon the conductors, between which it escapes. Priestley, who discovered them, had remarked that they are circular, and that they are formed upon metal plates, that receive the spark that comes from a pointed conductor, situated at a distance of $\frac{1}{10}$ in. Nobili, who studied them with care upon different metals, showed that they are due to internal heat, and even to a commencement of fusion, that is experienced by the metals. The circular form which they assume, is connected with the similar form of the brush, and is due to the dissemination of the electric filaments.

Notwithstanding these evident proofs of the high temperature of the spark, M. E. Becquerel was unable to discover in it any traces of radiant heat, which is chiefly due to its instantaneity. On this account also it is that it is unable, under ordinary conditions, to inflame certain very combustible bodies, which, like gunpowder, require, for ignition, the application of heat for a time, that must not be too short. But we may succeed in producing this inflammation, by compelling the discharge to pass through an imperfect conductor, which diminishes its rapidity, and so increases the duration of the spark; for example, through a string moistened with water. With a glass tube $6\frac{1}{4}$ in. in length, and 3 in. in diameter, closed at its two ends by corks, through which wires are passed, in order to conduct the discharge into the liquid, with which the interior of the tube is filled, we notice that, if this liquid is pure water or ether, we must charge a jar of $1\frac{3}{4}$ sq. ft. in surface, to 60° of the electrometer, to order to inflame the powder by the discharge of the jar; and to 30° only, if the liquid is alcohol; and that with acids, the inflammation no

longer occurs, even when it is charged as high as 80°. The differences are due to the fact, that the spark, in order to produce its effect, must possess at the same time a certain intensity and a certain duration, elements the converse of each other; and the relative value of which depends on the greater or less conductibility of the liquids.

Independently of light and heat, the electric spark developes in certain bodies, while traversing them, phosphorescence, namely, the property of appearing luminous in the dark, even when they were not so previously. Of all bodies, calcined oyster shells are they which most easily become phosphorescent, when they have been placed in the route of the electric discharge. However, many other substances, such as fluor spar, diamond, white marble, enjoy the same property of becoming phosphorescent, after the action of several discharges. However, the light alone of the sparks is able to produce the same effect, without its being necessary for the discharge to traverse the bodies; a property that we shall study in the eighth paragraph, when we shall be occupied with the electric light; of which we shall see that phosphorescence, after all, is only a particular case.

Calorific and luminous Effects of Electric Currents through imperfect Conductors.—Voltaic Arc.

Voltaic electricity, like that of the machines, is able to give rise to electric sparks; but in general these sparks are manifested when we put into contact, or, which is better, when we separate the wires or the metal plates, that are in communication with the two poles of the pile: it is more a phenomenon of voltaic ignition, than a veritable electric spark; it appears to arise from the heating that is suffered by the two points in contact of the wires, on account of the greater resistance which the current encounters, in this part of the circuit. Indeed, when we unite end to end, attaching them by simple hooks to each other, several wires, it is always at their points of contact that incandescence is first manifested, in order to its propagation thence into the re-

maining part of the wires. We have already spoken, in the second paragraph, of the phenomena of ignition or of deflagration, that are presented by the various metals: we will simply add, that the production of voltaic sparks is accompanied by a crackling, very similar to that of electric sparks, and that it occurs in rarefied as well as in common air, only with certain differences of appearance among oxidisable metals, that are due to combustion being in them less vivid.

Davy was the first who succeeded in obtaining voltaic sparks in liquids, by completing the circuit, by means of two small pieces of carbon. Bright sparks were seen to spurt, and there was at the same time an abundant production of gas. The extremities of the carbon appeared of a red white, even some time after contact. The liquid was indifferently water, fixed or volatile oils, ether, alcohol, nitric acid, sulphuric acid; the gases that were produced in this action varied with the nature of the liquids. It was a decomposition, arising more from the indirect action of the heat liberated at the point of contact of the two charcoal points, than from the decomposing action of the current, which scarcely traversed the liquid, seeing that the two pieces of carbon were in contact. In the following Chapter we shall return to the chemical effects of the voltaic spark, which must not be confounded with the direct decomposing action of the current.

M. Marianini, long after Davy's time, studied the production of voltaic sparks in liquids, but he operated under very different conditions. It was by using a very feeble pile, and a tube in the form of an inverted syphon, in which there was mercury, that rose in two columns in the vertical branches of the tube without filling them. Into one of the tubes was thrust a wire that was in communication with one of the poles of the pile; in the other, the wire communicating with the other pole was thrust into a liquid, such as water, or any other, placed above the bed of mercury. The thickness of the liquid stratum that the spark might traverse was very small, $\frac{1}{50}$ in. at most; its production was facilitated by a particular oscillatory motion that was suffered by the mercury, at the moment when the circuit is closed; and this motion, by con-

tinuing, produced a succession of sparks. The nature of the wires, by which the circuit is closed, is without influence over the phenomenon. It is not the same in respect to the nature of the liquid, within which the sparks spurt. It is the worst conductors that generally favour their production. We are able to make them appear even through oil, by taking care to thrust in the wire, as far as to contact with the mercury, and then sharply to draw it out: it is at this moment that the spark occurs, traversing the thin stratum of oil. By raising the wire thus, and lowering it until it is made to touch the mercury, a spark is every time obtained. With water and alcohol, the effects are similar; only the production of the spark in oil is accompanied by a peculiar noise, that does not occur with the other two liquids. M. Marianini had also noticed that the colour of the sparks is the same in liquids as in the air, and that the circumstances most favourable to their production are also the same in both cases; that thus they are more easily manifested between two carbon points, than between two metallic points.

Independently of these small sparks, which are more or less discontinuous, and are only manifested at contact or at very small distances *, voltaic electricity is able to give rise to a luminous phenomenon of the same kind, but much more remarkable, both on account of its intensity and its continuity. This is the phenomenon of the voltaic arc, discovered by Davy.

In order to obtain it, the illustrious philosopher made use of a pile of 2000 pairs of zinc and copper, each having 32 square in. of surface, thus presenting a total surface of 128,000 square in., charged with acidulated water. Having terminated the conductors, that were attached to each of the two poles, with pieces of charcoal about an inch in length and $\frac{1}{4}$ in. in diameter, he placed their ends, which were trimmed to a point, at the distance of about $\frac{1}{2\frac{1}{3}}$ in. apart, and he perceived a brilliant spark appear, at the same time the

* Mr. Gassiot, by means of a pile of 3500 small pairs of copper and zinc, charged with pure water, obtained between two brass discs, only $\frac{1}{50}$ in. apart, a series of sparks similar to those of the electrical machine.

charcoals became incandescent through half their length. He succeeded in separating the charcoals to the distance of more than 4 in. from each other, without causing the phenomenon to cease, which was manifested as a continuous bundle of fire, passing from one of the charcoal points to the other, in the form of an arc, convex above, probably on account of the ascending current of hot air. When any substance was introduced into this arc, it became incandescent; platinum melted in it like wax in the flame of a candle; sapphire, magnesia, lime,—all the most refractory substances,—entered into fusion. Fragments of diamond, points of carbon and of plumbago, disappeared rapidly, and seemed to evaporate in this focus, without appearing to undergo previous fusion.

In order to produce this phenomenon, an apparatus (*fig.* 214.) is employed, in which two metal rods, movable in

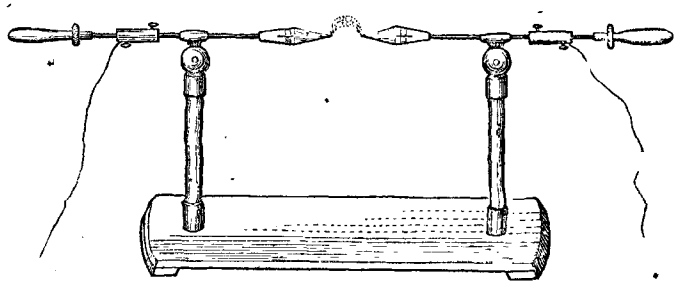

Fig. 214.

the horizontal direction like those of the universal discharger, are carried on two vertical insulating supports; the rods are each furnished with pincers, for receiving the charcoal points, and are respectively put into communication by means of conductors, with the poles of the pile. Handles of glass or wood, permit of the two charcoal points being withdrawn or approximated at pleasure in respect to each other. When we desire to produce the voltaic arc in vacuo or in very rarefied air, we make use of an apparatus (*fig.* 215.), formed of a glass globe, into which penetrate, through collars of leather, placed on the same horizontal diameter, the two rods furnished with charcoal points. A stop-cock, fixed to the metal tube, that serves as the support to the globe, enables us

to produce and to maintain in it very rarefied air; and at pleasure to introduce into it different gases, under greater or less degrees of pressure.

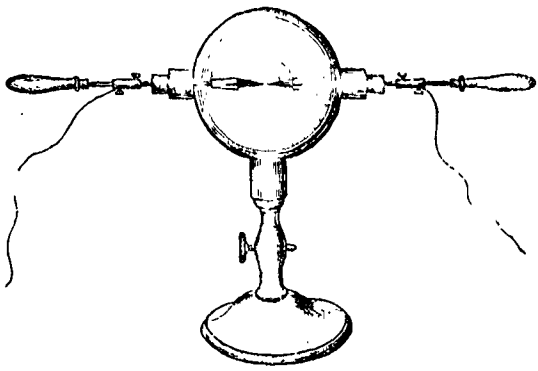

Fig. 215.

Davy had already remarked, that the phenomenon of the voltaic arc is produced in vacuo, as well as, and even better than, in air; a proof that the combustion, with which it is attended in air, is not the cause of the heat and light that are there developed. He even succeeded, by separating the points, in giving the arc in vacuo a length of 6 or 7 in., namely, almost the double of what it presented in air: furthermore, the light was quite as vivid, and the heat quite as great: for the carbon was powerfully incandescent; platinum wire melted with a brilliant scinctillation, and fell in globules to the bottom of the globe.

A long time after Davy's brilliant experiments, Professor Sillimann, on repeating it with Dr. Hare's pile of cylindrical pairs, called by him a deflagrator, observed some very remarkable molecular phenomena. He placed plumbago in communication with the positive pole, and a piece of well-baked carbon, with the negative pole. Globules of melted plumbago were soon perceived; and also a hemispherical excavation on the plumbago itself: whilst the carbon was elongated on the side of the plumbago, and the black matter, that was accumulated there, presented the appearance of fusion, not into globules, but into striated fibres. This

matter evidently owed its origin to the plumbago of the positive pole, which had been transported in the state of vapour to the negative pole. On interchanging the poles, very few globules were seen to be formed upon the plumbago, and none upon the carbon; but this latter was rapidly hollowed; the plumbago, on the contrary, was elongated by the matter that accumulated at its extremity; and which, when seen by means of the microscope, presented an aggregation of little spheres, with the character of a perfect fusion, and with a decided metallic brilliancy. The spheres seemed to be formed by the condensation of a white vapour, similar to that of the oxides arising from the combustion of different metals. The globules themselves, when powerfully heated in oxygen gas, gave carbonic acid, and a residuum of iron, attractive to the magnet. Mr. Sillimann thought he found some analogy between these melted carbonaceous substances and the diamond; but the globules in question scratch glass alone, are attractive to the magnet, and do not experience any alteration in oxygen at the highest temperature; whilst ordinary diamond is not attractive, scratches all bodies, and burns in the air at a red heat. It is therefore very probable that the former are due to the nature of the ashes arising from the iron contained in the plumbago.*

With regard to the passage of matter from one pole to the other, M. Sillimann observed it very well. By protecting his eyes with a green glass, he distinctly saw the matter pass under different forms to the negative pole, and collect there as dust would have done, that had been driven by the wind; he also noticed at the positive pole, a species of trepidation, produced as if by the impulsion of an elastic fluid striking against the opposite pole. I have myself observed this latter phenomenon

* Nevertheless, M. Despretz succeeded, by employing for a negative electrode a sort of nippers, formed of fine platinum wires, and a fragment of very pure carbon for the positive electrode, in obtaining, by the formation of the arc between these two electrodes, some very brilliant points at the extremities of the platinum wires, which, when seen by the lamp used by jewellers, presented all the appearance of small fragments of diamond. He also succeeded in procuring similar fragments, by substituting a liquid hydro-carbon for the solid carbon. We shall return to this when we are engaged with the chemical effects of dynamic electricity.

without having need of a very powerful pile; a Grove's pile, of ten pairs, is sufficient. The two carbon points must be fixed to two metal rods, bent into a horse-shoe, and sufficiently elastic that the two points may be in contact by their two extremities, without there being the least pressure of one against the other. Immediately the current is established, the light darts between the points, and a rapid series of, as it were, small detonations, is heard, which, in their communication from the carbon to the metal, make the latter vibrate, so as to produce a sound, and even to render the vibrations sensible to the touch. This noise arises neither from the electrical attractions and repulsions, nor from a friction, that might occur between the points; for it is the same with the softest carbon, as the carbon of poplar, as it is with two points of the hardest carbon, such as that collected from gas-retorts. It is a species of regular crackling, that occurs among the molecules of carbon, traversed by the current, and is connected with the rending off, and the transport of these molecules. This noise is no longer heard, when spongy platinum is substituted for the carbon points; although there is in this case, as with carbon, a transport, of which I have convinced myself, of particles, from the positive to the negative pole. These particles, by their association, form, as it were, species of ramifications, which the high temperature produced by the current, renders incandescent, and consolidates by fusion, so that they may be easily detached, without their form being altered.

By this last example, we perceive that the voltaic arc may be produced, not only between two points of carbon, but also between two metal conductors, such as spongy platinum; it is not even necessary that the metal be in the state of sponge. Thus it may be established between two points of forged platinum; but then it is not so long, and it requires a more powerful pile for its production.

The appearance and the length of the arc vary considerably, with the nature of the electrodes between which it is manifested. Thus with wood charcoal well burnt and

quenched in water*, the light is much more vivid, and is moreover whiter than with coke; but this carbon requires a pile of a somewhat higher tension. Daniell, with a pile of seventy pairs, copper and zinc, charged with sulphate of copper and water, acidulated with sulphuric acid, obtained a very brilliant arc either with two points of this carbon, or with one point of carbon, and one of platinum. M. Despretz, in a series of beautiful experiments, made with a very powerful pile, had found very variable lengths for the arc, according to the number and arrangement of the Bunsen pairs, which were the kind employed by him. He produced the arc in air; enclosing it however within a glass cage, having observed that the agitation of the air greatly deranges it. He affixed the carbon points, which were of coke properly prepared, to the extremity of rods of copper of $\frac{2}{3}$ in. in diameter: the arc was vertical. The following are the lengths: 25 pairs, 1 in.; 100 in parallel series of 100, $7\frac{1}{4}$ in.; 24 series of 25, 45 in.; the 600, in succession one after the other, $6\frac{1}{4}$ in.; pole + below $2\frac{1}{4}$ in.; pole + above 3 in. M. Despretz always observed certain obscure parts in the arc. Finally, he made some curious observations on the very powerful soldering, that occurs between the carbon rods, of which the arc is formed when they are placed in contact; especially between those, that have been prepared by calcining sugar-candy.

In general, in order to obtain the arc, we must commence by putting the two points into contact; then, when the point of contact has become incandescent, the two electrodes are gradually drawn apart. However, Daniell succeeded in determining the arc, without previously placing the electrodes in contact, simply by passing between them a powerful electric spark. This is the cause that, with piles of very high tension, which are able to give a spark at a distance, the arc is obtained between two points, without there being any need of their being made to touch.

* Wood charcoal, quenched in mercury, is sometimes employed; with carbon of this kind, the arc may be produced with a much less powerful pile, but its light is less brilliant; and there is a formation of vapours of mercury that disturb the phenomenon.

Fizeau and Foucault, when operating with a pile of eighty Bunsen's pairs, one of the electrodes of which was carbon, and the other a metal rod of silver or of platinum, remarked differences in the length of the arc and in its duration, according as the metal or the carbon communicated with the negative or the positive pole.

Mr. Grove had already observed that the length of the arc and its brilliancy depended upon the nature of the metals between which it is produced, the two electrodes being in each case of the same metal. The following is the order in which he classed them, in this relation, commencing by those which give the longest and most brilliant arc, and supposing that the phenomenon occurs in the air: potassium, sodium, zinc, mercury, iron, tin, lead, antimony, bismuth, copper, silver, gold, and platinum. Mr. Grove had also remarked that a part of the substance, whence the luminous arc escapes, is projected from the positive to the negative pole, and that it is in the state of metallic powder, if the ambient medium is vacuum, hydrogen, or nitrogen, and in the state of oxide, in oxygen or in air.

However, the fact of the transport of molecules from the positive to the negative pole is not so general as had long been supposed. M. Van Breda, when operating in vacuo, and determining the voltaic arc, without previously placing the electrodes in contact, but by means of a powerful electric discharge, has obtained a transport equally in both directions, cording to the relative nature of the two metals between which the arc passes. With two balls of iron, he found that after the experiment, the positive ball had lost $4\frac{3}{4}$ grs. and the negative, instead of having gained, had also lost nearly a grain. With an iron ball, and a cone of coke, prepared like the coke that is employed in the Bunsen piles, the iron lost very nearly the same amount, whether it was positive or negative; and the coke lost more in the former than in the latter case. An experiment, which proves clearly that an emanation of particles may take place equally from both poles, although more powerfully from the positive to the negative than from the negative to the positive, consists in

placing between two copper balls, serving as electrodes, a thick and insulated plate of iron. The experiment is made in vacuo, and the arc is brought about by an electric discharge. The positive ball gains in weight about a grain, and the negative 5½ grs. They are both covered with molecules of iron, which are derived from the plate. It seems therefore that matter is repelled at the same time from both poles; or rather that there exists a repulsion among the metal particles that conduct the current.*

I have myself studied the formation of the voltaic arc, by employing electrodes of different metals, either both cut into points, or one alone in a point, the other having the form of a plate. In order to measure carefully the length of the arc, I employed two apparatus, one for measuring it in the air, the other for measuring it in vacuo, or in different gases. This latter apparatus might, in strictness, have served both purposes; but I preferred to have one in which the arc might be produced in the open air.

The first apparatus (*fig.* 216.) consists of a groove,

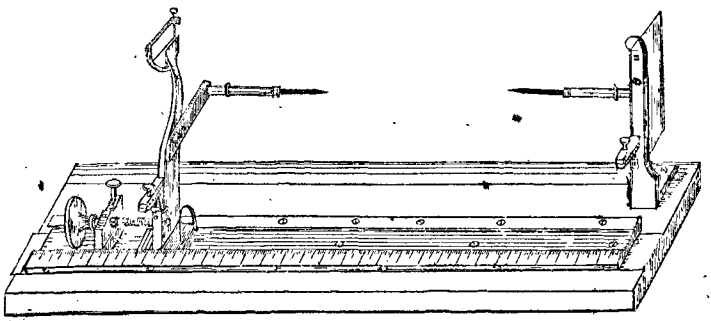

Fig. 216.

carrying on one of its sides a linear division, in which there slides truly with friction, a metal support, that carries a

* We have clearly seen from Ampère's laws, Vol. I. p. 223., that all portions of the same current repel each other; and that this repulsion, which is manifested under the form of a simple movement, when a part of the current is mobile, ought to be able to give rise to a separation or disaggregation of particles, when the conductor, not being mobile in any of its parts, the current is very energetic.

pair of horizontal nippers, to which may be adjusted conducting points of different natures; a micrometer-screw enables us to measure, with great accuracy, the quantity by which the support, and consequently the point, that it carries, is made to advance or to recede. At one end of the groove is a fixed metal support, to which is adapted either a similar point to the former, or a conducting plate, so that the arc may be made to pass either between two points or between a point and a plate. The divisions of the micrometer-screw enable us very accurately to measure the distance between the two points or between the point and the plate; and consequently the length of the arc. The second apparatus (*fig.* 217.) consists of a bell-glass, that is placed upon the table of an air-pump, in order to rarefy the air, and when required to introduce into it any gas, by means of a stop-cock adapted to the mounting, which being situated above the bell, carries itself a collar of leathers, that is traversed by a metal rod, at the end of which is a binding screw, for receiving a metal point. This rod may be lowered or raised to an amount, which may be very accurately measured by means of a circular division traced upon the circumference of a disc, that moves with the piece provided for raising or lowering the rack-work, with which the rod is furnished. A fixed metal support is placed at the bottom of the bell-glass; it carries either a vertical point, or a horizontal plate, so that the arc may be established with this apparatus, as with the preceding one, either between two points or between a point and a plate.

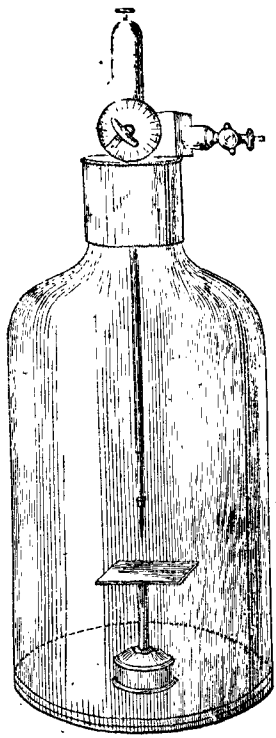

Fig. 217.

Having taken for one of the electrodes a plate of platinum, I

employed successively for the second electrode points of different natures. With a platinum point, the arc is very short, especially if the point is the negative electrode. In air rarefied to about $\frac{1}{10}$ in., the point could not be separated more than $\frac{1}{25}$ in. without the arc breaking. The experiment was made with a Grove's pile of fifty pairs, feebly charged. With the same pile, powerfully charged, there was formed upon the platinum plate, employed always as the positive electrode, a perfectly circular bluish spot; it was also formed in air under the ordinary pressure, but it had then a diameter one half less. In hydrogen, it is not formed at all, a proof that its production is the result of an oxidation. When the platinum plate is used as negative electrode, it is also covered with a circular spot; but this spot is formed of a heap of small grains of platinum, and remains white; like the blue, it is much larger in rarefied, than in ordinary air. With regard to the platinum point, it very rapidly becomes highly incandescent, when it is positive; its extremity enters into fusion, and finishes by falling upon the plate, forming there a perfectly spherical globule; whilst when it is negative, it is but little heated and does not melt; on the other hand, the plate, which is then positive, becomes red-white, and runs a risk of being perforated, unless it is very thick. When a point of coke is substituted for the platinum point, the plate remaining still platinum and positive, we obtain an arc of double the length of the one, that had been obtained with the platinum point. The arc itself, instead of presenting, as before, a cone of light, having its base on the plate and its summit on the point, is composed of a bundle of luminous jets, starting from different points of the plate to impinge upon different points of the coke; finally, the heat developed upon the platinum plate is so much more considerable, that the plate is rapidly melted and perforated. The pile, in these experiments, is exactly of the same force as when the point is of platinum, instead of being of coke. By this we plainly perceive the very great influence that is exercised by the negative electrode, whose function is far from being purely

passive; for we have merely to change its nature, in order to modify in a very notable manner all the details of the phenomenon. When the coke is positive and the platinum plate negative, the arc is not so long, especially in air, in which it is sensibly shorter than in vacuo; but the coke point is considerably heated, and becomes rapidly incandescent in its whole extent.

By employing successively for electrodes iron, copper, silver, and german-silver, we observe, when one of the electrodes is a point, and the other a plate of the same metal, that the point is incandescent throughout its length, if it is positive, and that it is heated at its extremities alone, if it is negative. With regard to the plates, they present very decided cavities, surrounded by coloured circles, when they have been employed as positive electrodes in rarefied air. With mercury taken as one of the electrodes, the luminous effect is of the most brilliant kind; the mercury is in a state of extreme agitation, rising into the form of a cone, when it is positive, and presenting a cavity below the positive point, when it is negative.

A point worthy of notice is the difference that exists in the temperature that is acquired by the two points, between which the voltaic arc is formed, according as they are of the same or of a different nature. When they are of the same nature, it is always the positive point that alone becomes incandescent in all its extent; if they are of a different nature, it is the least conducteous that is heated, as well when it is negative as when positive. Thus if the positive point is silver and the negative platinum, it is the latter that becomes incandescent, and the silver is much less heated. Things happen, therefore, as they do in a circuit completely closed: it is the portions of the circuit, that present the greatest resistance to the current, that are most heated; first the portion that forms the arc itself, then the metal that is the worse conductor. But, when the conductors on each side of the arc are identical, the heating, instead of being uniform, is much more considerable for the positive side; a phenomenon which, in connection with the disaggregation that

occurs upon the same side, seems to indicate that the positive electrode suffers, on the part of the current, a much more energetic action than the negative.

M. Matteucci, by plunging for a certain time the two points, between which the arc is established, into masses of water separated, and taken at the same temperature, found that the difference of temperature between the two points is greater, according as they are formed of a material that is less conducteous, and more easy of disaggregation. But, what is very curious, is that, in hydrogen gas, the difference becomes very small, which is probably due to the same cause that diminishes the heat of a platinum wire traversed by the current, when this wire is surrounded by hydrogen, namely, to the cooling power of this gas, which increases the conductibility of the part of the circuit that is plunged into it. Moreover, this unequal heating may take place by the simple contact of the two conductors, only the difference is greater when the contact is less intimate; it is diminished by pressing the two conductors strongly against each other: on the other hand, it is augmented by covering one of the surfaces in contact with a slight film of oxide, of graphite, or of carbon powder; the formation of the arc is further facilitated by artificially heating the positive electrode.

M. Tyrtow, by employing mercury as one of the electrodes, and making use of wires of different kinds for the other, remarked that, whenever the mercury is negative and the wire positive, the latter becomes red-hot and melts when its extremity is placed in contact with the mercury; whilst when the wire is negative, and the mercury positive, at the moment of contact some bluish sparks are alone apparent, but the mercury then undergoes a powerful evaporation. Similar experiments have been made by various philosophers, by substituting decomposable liquids for mercury; but then the luminous and calorific effects are complicated by electro-chemical phenomena; but we postpone the study of these to the following Chapter.

It is also to the difference of temperature of the two electrodes, that Mr. Gassiot's curious experiment must be attributed, in which, when placing two wires across, for instance copper wires, that are in communication with the poles of a powerful pile, the positive wire is perceived to become red for a distance of a couple of inches beyond the crossing point, even till fusion occurs; whilst the negative is incandescent only in the portion traversed by the current. It is evident that in this instance, there is at the point of contact, a commencement of the formation of the voltaic arc, the more so as, on separating the wires a little from each other, the arc appeared between them. The positive conductor is here the positive electrode of the arc; and, in this capacity, it becomes much more heated than the negative, which causes it to become incandescent, not only in the portion that is traversed by the current, but even to a small distance beyond this portion.

As M. Matteucci observed, the arc is generally composed of a central part almost cylindrical, whose bases rest upon the polar extremities, and which shines with a white and very intense light; this part is enveloped in a more rare luminous matter, of a spheroidal form, the colour of which changes with the nature of the points whence the arc emanates, and with that of the medium that it traverses. The central part is composed of a matter, in which the electric current is propagated, as in a liquid conductor; for proof of this, we have merely to thrust into it the fine ends of two platinum wires, coming from two glass tubes, and fixed to the extremities of a galvanometer. At the moment when the platinum wires arrive at the central part of the luminous arc, the elevation of the deviation of the needle of the galvanometer indicates the presence of a powerful derived current. Furthermore, we have merely to introduce a voltameter into the circuit of the voltaic arc, to have evidence that the current is propagated in it in a continuous manner. We are even able, by the indications of the voltameter, to estimate the resistance opposed by the arcs produced with points of different natures, placed at variable distances. Thus, when operating with a pile of 60

pairs of Grove's, it is found that the current, by its passage in the voltameter for 60 seconds, liberates in it quantities of gas equal to 3·4, 2·6, and 2·3 cubic inches, for distances, between the points of coke in the arc, corresponding to ·07, ·11 and ·15 in. With two points of silver, which alter less promptly than those of carbon, 3·6 cubic inches of gas is obtained, at a distance of ·11 in. between the points, and 2·8 cubic inches at a distance of ·23 in. With points of different metals, forming luminous arcs of ·11 in. in length, there is found in the voltameter, after passing the current through it for 60 seconds, 1·4 cub. in., if the points are of copper; 1·5 cub. in. if they are of brass; 1·6 cub. in. if they are of iron; 1·7 cub. in. if they are of coke; 2·1 cub. in. if they are of zinc; 2·7 cub. in. if they are of tin. When the points touch and there is no arc, 2·8 cub. in. are obtained. It evidently follows from this that the conductibility proper of the arc depends, less upon the conductibility of the metals of which the points are formed, than upon their facility of melting and disaggregating, and consequently upon the quantity of matter that disappears in the experiment.

If a metal plate is placed between the two points, so as to be situated in the middle of the arc, the formation of which is excited by an electric spark, we notice that the central part of the plate commences by entering into fusion, and globules dart from both sides, towards the points, at the same time that similar globules dart from the points towards the plate; the inner part of the arc, which gives it the spheroidal form, appears to be produced by the still more divided matter, that is the result of the destruction and combustion of these globules; when the arc is produced in a liquid, this matter is not seen to be volatized and divided, seeing that it is dispersed n the liquid; the central part alone is perceived, which, on the other hand, is less distinct with carbon points, on account of their great facility of disaggregating.

It would seem that the formation of the arc is the result of the contrary electrical states, that are possessed by the polar extremities before the circuit is closed, which may be mani-

fested by an attraction and a spark *, and which subsisting when the arc is once formed, determine at a certain distance, that is always very small, between the points a series of sparks and a chain of molten matter, or of incandescent particles, detached from the pole. The same phenomenon ought, indeed, to exist in all parts of the circuit, since it is thus that the propagation of the current takes place; but it produces mechanical effects in the portion of this circuit, similar to those in which the voltaic arc is manifested, and in which the resistance is greater and the distance of the particles more considerable.

The spheroidal form of the arc is the result, like the phenomenon that is produced with the spark of the machine in the experiment of the electric egg, of the mutual repulsion of the parts detached from the same polar extremity, joined to the attraction exercised over them by the other pole. We may even see, by passing a series of sparks between two metal points plunged into essence of turpentine, that holds in suspension very fine particles of cork or carbon, that these particles group themselves between these points; forming a mass of a spheroidal form, composed of filaments that go from one point to the other, and each of which is formed by a chain of these molecules, between which small sparks pass. We have already seen in the first Chapter of this Part, that the distribution of currents in a liquid conducting mass seems to take place under the form of filaments abutting on the two poles, and forming between them a spheroid. We shall see new proofs of this, when we are occupied with the chemical effects of the current.

A phenomenon that is of a nature to confirm what we

* Mr. Gassiot, as we have seen, had obtained with a pile of 3500 pairs of zinc, copper, and water, at the polar extremities, electrical charges of such strength, as to give for several days in succession, sparks passing at a distance of $\frac{1}{30}$ in. and succeeding each other very rapidly. M. Matteucci, by connecting the poles of a Grove's pile of fifty to sixty pairs, with two brass rods, each carrying at its extremity a sheet of gold-leaf, perceived an attraction to be manifested between these leaves at a distance of an inch or so; and, if these two leaves are made very short and are brought very near together, they are seen to be attracted at the moment when the arc closes the circuit; at the same time a spark passes, and the luminous arc is generally established.

have been saying on the nature of the voltaic arc is the influence that is exercised upon it by magnetism. Arago had suspected this influence immediately after Œrsted's discovery; Davy proved it soon after, by bringing a powerful magnet near a voltaic arc formed by two carbon points, and from 1 to 4 in. in length, according to the degree of rarefaction of the surrounding air. The arc or luminous column was attracted or repelled with a rotatory movement, according to the position of the pole of the magnet, and the direction of the current. The action was more energetic, when the air through which the arc was produced was more rarefied, and consequently the arc itself was more extended.

By employing an electro-magnet instead of a magnet, the effect is much more decided, and the arc may even be broken, by causing a too powerful attraction or repulsion to break the chain of particles, that establish the communication between the two poles, and that constitute the movable conductor, upon which the magnetic force is acting. M. Quet, having produced a vertical voltaic arc, perpendicularly between the two vertical polar faces of an electro-magnet, saw this arc transform itself into a horizontal dart, like that which is produced by blowing upon a flame with a blow-pipe. This dart may attain a length eight or ten times greater than the arc 1 or $1\frac{1}{2}$ in. in length, for example when the latter is only $\frac{1}{6}$ in. Particles of carbon are seen to be projected by the action of the electro-magnet, in the direction of the dart, when the carbons are incandescent on the side of the points themselves from which the arc emanates. The change of direction of the dart, when the direction of the current or the poles of the electro-magnet are changed, plainly indicates that this effect is due to the repulsive action of one of the magnetic poles, combined with the attractive action of the other, upon the current that is transmitted by the arc. This is confirmed by the convex form that it assumes in the direction of the dart, when the poles of the electro-magnet are too far off to allow of the dart itself being formed. We may add that its formation is attended by a peculiar whizzing, which lasts as

long as the dart; and that at the moment when it ceases, there is produced a very powerful detonation.*

I had already noticed, before M. Quet, this double noise, in a detailed study that I had made of the action of magnetism upon the voltaic arc; and I had shown that it is connected with the molecular modifications that this action brings upon the matter itself of this arc. I had at first remarked that if two rods of soft iron, serving as electrodes, are each placed in a bobbin, formed of a thick copper wire, the voltaic arc, that occurs between these two points, ceases at the moment when the iron rods are magnetised, by passing a powerful current into the bobbins; and that it recommences, if we take care to interrupt this current before the points have become cold. The arc itself cannot be established between two points of iron when they are magnetised, except when they are much nearer; and its appearance is quite different. The particles that are formed seem to detach themselves, not without difficulty, from the electrodes; sparks dart with noise in all directions; whilst formerly there was a very vivid light without spark and noise, accompanied by the transport of a liquid mass, which was brought about with the greatest facility. The phenomenon takes place in the same manner whether the two rods of iron present at their ends, between which the luminous arc passes, the same or different magnetic poles. We must also remark that the positive electrode produces, when powerfully magnetised, at the moment when the arc is established between it and a negative electrode of any nature, a sharp hissing, altogether similar to what occurs to steam in locomotives; the noise ceases immediately with the magnetisation.

In order the better to study this kind of effect, it is preferable to employ a powerful electro-magnet. I did this and placed upon one of its polar surfaces a metal plate, and vertically over it a metal point so as to establish the voltaic arc between them. The plate and point being both

* This detonation is often very powerful, also, in induction sparks, which are veritable instantaneous voltaic arcs.

of platinum, and the plate being positive, as soon as the electro-magnet is magnetised, whilst the arc is in existence, a very sharp hissing is heard; and it is necessary to bring the point very near to the plate in order that the arc may continue. If the plate is negative and the point positive, the arc can no longer maintain its vertical position; it is projected towards the edges of the plate and is immediately broken; every time its rupture occurs, it is attended by a dry and instantaneous noise, similar to the discharge of a Leyden jar.

The same effects are observed, by employing a plate and point of any metal, provided the plate and point are of the same metal, and that the latter is not too fusible. Copper, and especially silver, present a remarkable peculiarity; it is that the plate preserves on its surface the impression of the action that it suffers under the influence of the electro-magnet. Thus, when it is positive, the portion of the surface that is beneath the negative point presents a spot in the form of a helix, which seems to indicate that the melted metal in this portion underwent a gyratory motion around a centre, at the same time that it is raised in the form of a cone. The helical curve is, moreover, in its whole length bordered by small ramifications, perfectly similar to the brushes that are developed by the traces of positive electricity, that comes from the knob of a Leyden jar. When the plate is negative and the point positive, the traces are very different; there is a circle of a very small diameter from which arises a line, more or less curved, that forms a species of tail to the comet, of which the small circle would be the nucleus; the direction of the tail depends upon the direction in which the arc has been projected.

On producing the arc between two points, very near to the electro-magnet, between its two poles for example, we may easily bring about either the sharp hissing or the series of detonations; the latter are even sometimes so strong as to resemble distant discharges of musketry; it is merely necessary that the electro-magnet be very powerful, and the current by which the arc is produced, very intense. With

a point of platinum, and one of copper, the hissing is obtained, when the platinum is positive, and the detonations, when the copper is positive. This is due to platinum becoming much more heated than copper when positive. It is easy to prove that, in order to obtain the hissing, it is necessary that the positive electrode attain a temperature, capable of making it undergo a commencement of liquefaction; if this is not the case, we obtain merely detonations: I have satisfied myself of this, by numerous experiments made with different metals. In order to obtain the hissing, the precaution must be taken of maintaining the arc as continuous as possible, when once the positive electrode is well incandescent; whilst, in order to obtain detonations, one of the electrodes must be held in the hand, and the arc must be established and interrupted frequently, taking care that the temperature of the points does not rise too much. These results appear to point out to us that the hissing is due to the transport of the matter of the positive electrode, more or less liquefied, whilst the detonations arise from the tearing off of these same particles, when the substance that is disaggregated is not highly heated. But what is very extraordinary, is, that this hissing and these detonations take place only when the arc is under the action of the magnet. Can it be simply the effect of the attractive and repulsive action of the currents of the magnet upon the series of particles which, forming the arc, constitute a conductor, more or less mobile, traversed by the current? Can it be the result of a modification, brought about by the influence of the electro-magnet upon the molecular constitution of the electrodes? I am rather disposed to think that, under the powerful influence of the electro-magnet, the molecules which transmit the current, in forming the electric chain, assume forced positions, due to electro-dynamic action; and that the hissing is the result of this constraint, impressed upon the molecules that come off from the electrodes, whilst the detonation is the effect of their return to their state of molecular equilibrium. The following experiments appear to me of a nature to corroborate this opinion, at the same time they seem to confirm the ideas, which we have put

forth in the preceding Chapter, upon the mode of propagation of the electric current.

If we place in the axial, or equatorial, or intermediate direction, above the poles of a powerfully magnetised electro-magnet, prismatic bars of tin, zinc, lead, and bismuth of $\frac{3}{4}$ in. square, and about 20 in. in length, and cause a discontinuous current to traverse them, derived from a pile of from 5 to 10 pairs of Grove's, we hear very distinctly a sound composed of a series of blows, corresponding to the interruptions of the current. They give out no perceptible sound, so long as the electro-magnet is not magnetised. The same effect is produced with rods of copper, silver, and platinum. Tubes of all these same metals give out still more decided sounds than solid cylinders; wires wound in a helix around a wooden cylinder, vibrate in like manner; a wire of lead, arranged in this manner, is able in particular to give out a very powerful sound. An ordinary magnet produces the same effect as an electro-magnet. It is the same with a helix, traversed by a powerful continuous current, in the axis of which is placed the bar, the tube, or the wire, through which the discontinuous current is transmitted. With a double helix, formed of two thick copper wires, covered with silk and wound one exteriorly to the other, we obtain a sound of remarkable intensity, by causing the continuous current to pass through the exterior wire, and the discontinuous through the interior; in the converse case, the sound is much more feeble, which is due to the magnetic action of a current in a helix, being almost null exteriorly, whilst it is very energetic interiorly.

The effects, that we have been describing, cannot be attributed to a dilatation, arising from a heating brought about by the current, since they take place with conductors of too large dimensions, and with too feeble a current, for us to admit that there is the slightest elevation of temperature. Moreover the sound is produced only so long as the electro-magnet is acting at the same time that the current is being transmitted. Neither can we admit that the production of the sound is the result of a mechanical flexion, occasioned by the attractive or the repulsive action of the electro-magnet

upon the conductor traversed by the current; the dimensions of this conductor exclude this interpretation, which moreover cannot be reconciled with the fact that bodies so little elastic as lead and well-burnt vegetable carbon give rise to the same phenomenon, as does a column of mercury, contained in a glass tube, an inch in diameter, and 10 in. in length.* All these phenomena appear to me to be the result of the action of the electro-magnet upon the small voltaic arcs, that occur from molecules to molecules, in the interior of a conducting body, traversed by an electric current. When the electro-magnet acts upon all the visible voltaic arcs, it is not necessary, in order to the production of the sound, to render the current discontinuous; because it is already so of itself, the arc being formed of a series of discharges, that succeed each other more or less rapidly. It is not the same, when the current traverses good conductors, such as metal rods; it is then necessary to render it discontinuous, in order that the particles may have time to recover their natural position between the passage of two successive currents, and may thus acquire an oscillatory movement around this position, a necessary condition, in order that the action of the electro-magnet may determine a sound, and which is found fulfilled naturally with the luminous voltaic arc.

In fine, the oscillatory motion and the production of sound, which is it consequence, appear to me to be a molecular phenomenon, arising from the conflict established between the position, which the action of the magnet tends to impress upon the molecules, that form the electric chain, and that which the particles possess naturally. This conflict, very apparent to the eye, as well as to the ear, when it takes place in the particles, of which the luminous arc is composed, becomes sensible by sound alone, when it occurs with molecular arcs, or discharges that take place from particles

* When mercury is placed in an open trough, at the same time that a sound is heard, a particular vibratory motion is seen on its surface, very different from the gyratory motion that it manifests under the influence of the poles of a magnet, when traversed by a continuous current.

to particles. But, except in its magnitude, it is no less an analogous phenomenon; which confirms, as we have already remarked, the idea which we have already laid down that the propagation of the current takes place in conductors by a series of discharges from molecules to molecules, similar to those which are brought about at finite distances between two conductors, and which we have just been studying, under the name of voltaic arcs.

General Considerations on Electric Heat and Light. Special Properties of this Light.

The study that we have been making of the electric spark and the voltaic arc, have demonstrated to us that, under these two forms, the production of light and heat by electricity is connected in a remarkable manner with the motion of the particles of bodies. On the other hand, the recent researches of Joule, of Clausius, and of Thomson have led philosophers to regard heat as resulting from a rotatory motion of the particles about an axis; and we have ourselves considered this hypothesis as calculated to explain the polarity of atoms.* Might it not then be possible that the cause of the heat, and consequently the light, that are generated by the reunion of the two electricities, brought about under the form of discharge or current, may be not in the fact itself of this reunion, but in an increase of molecular motion, that might result from the transmission of electricity? This motion, it is true, is not apparent in the phenomenon of the heating, and the incandescence of good conductors, such as wires, as it is in the spark and in the voltaic arc. However, it is manifested, even in this case, by the molecular modifications which are experienced by the wires that have been rendered incandescent by the effect of discharges.† Moreover, it would

* Vol. II. p. 48.

† An experiment which would seem to have demonstrated that the heat liberated by the current is due to a motion having a certain direction, was that in which attempts were made to pass at the same time through the same wire, in directions contrary to each other, two energetic currents of the same intensity, and each capable separately of making that wire red-hot. It was found that,

seem to us that the best proof, in favour of the existence of this motion, independently of the production itself of the heat, exists in the general fact of the sounds that are given out, and consequently of the vibrations that are experienced, by all conductors which transmit discontinuous currents, when placed under the influence of powerful electro-magnets.

With regard to the theory that attributes the liberation of heat and light in a direct manner to the reunion itself of the two electricities, we find an objection against its generality, in the important fact, discovered by Peltier, proved and studied by several other philosophers, that this reunion sometimes produces a reduction of temperature. Peltier had demonstrated this curious property of the current, by placing in the interior of the bulb of an air thermoscope, instead of a platinum wire as in Riess's apparatus (*fig.* 193. p. 216.), a rod $\frac{1}{10}$ in. in diameter, consisting of two small cylinders, one of bismuth, the other of antimony, applied end to end against each other, so that their surface of contact was almost at the centre of the bulb. He found that the electric current of a single pair, transmitted through the rod, reduced the temperature of the point of contact thirty-seven divisions, when it was going from bismuth to antimony, and raised it about forty-five when travelling from antimony to bismuth. Lenz justly remarked that the effect of the cooling is diminished in the manner in which Peltier operated, by the heating that the passage of the current determines in the bar itself of bismuth, as indeed he proved. In order to avoid this inconvenience, he soldered one after the other two quadrangular bars of bismuth and antimony, each $4\frac{1}{2}$ in. in length, and having a transverse section

under these circumstances, the wire remained perfectly cold; a proof, it was thought, that the two motions, guided in opposite directions, neutralised each other. But it is easy to see that in this mode of operating, the wire, instead of being traversed by two opposite currents, is not traversed by either. In fact, the experiment is reduced to this; namely, that when two piles are connected by their opposite poles, so as to form a complete circuit, a wire which unites the two conductors, establishing communications between the poles, is not traversed by any current; which must be the case; since scarcely even would a feeble derived current be transmitted by the wire. The experiment, therefore, is in no way conclusive, in favour of the existence of a molecular motion, but it is not contrary to it.

of ·38 sq. in. he then, at the point of soldering, pierced a hole, into which he introduced the bulb of a small thermometer, taking care entirely to fill with iron filings the upper part of the hole, that remained empty. By passing through this metal rod the current of a simple pair of zinc and platinum of about 155 sq. in. surface, he found that the thermometer fell 7°·2, when the current was going from the bismuth to the antimony; and that, on the contrary, it rose several degrees, when the current was travelling from the antimony to the bismuth. Having filled the hole of the soldering with water, and having covered the rod, except at the soldering point, with melting snow, so that the temperature of all the apparatus, including the water, was maintained at 32° Fahr., he succeeded in freezing the water contained in the hole, and even in lowering its temperature to 24° Fahr., by causing the current to pass from the bismuth to the antimony for five minutes. Without the passage of the current, the water did not freeze; and its temperature was maintained merely at 32° Fahr.

The curious phenomenon that we have just been pointing out is connected with a more general fact, namely, the variation of temperature that is brought about by the passage of an electric current at the point of contact of two heterogeneous conductors, soldered end to end. M. Peltier observed that, for the greater part of the metals, the elevation of temperature is always much greater at the point of contact of two wires, when the current passes from the worse to the better conductor, than in the reverse case; and the difference may become such that, in certain cases, instead of an elevation there is a fall of temperature, as we have remarked; but then two conditions are necessary in order to obtain this latter phenomenon,—the first, that one of the metals, at least, shall be crystalline; the second, that the transmitted current shall have a feeble intensity.

M. Frankenheim, who made a profound study of these phenomena, justly distinguished this variation of temperature, which takes place at the limit of the two conductors, and which he names *secondary*, from that which occurs in the whole circuit. The former depends upon the direction of the

current, whilst the latter is independent of it; it is proportional to the simple intensity of the current, whilst the latter is proportional to the square of this intensity.

Moreover, the effects, for the first time observed by Peltier, are connected with a phenomenon that we have not yet studied,— that of the production of thermo-electric currents, which are developed by heating and cooling alternately the points of contact of small heterogeneous metal rods, soldered end to end, one after the other, so as to form an entire metal circuit. In fact, on heating the point of contact of a bar of antimony and a bar of bismuth, a current is determined, which travels directly from the bismuth to the antimony; and on cooling it, a current is obtained which travels in like manner directly from the antimony to the bismuth; that is to say, that the current produced by these variations of temperature, has a direction precisely contrary to that of the current that would produce these same variations. This opposition seems therefore to indicate that the exterior current, that is introduced into the rod composed of two metals, produces in them a molecular motion, acting in a contrary direction to that which is determined in them by heat, and hence arises the fall of temperature, which is so difficult of explanation otherwise. But it is only in the Fifth Part, devoted to the sources of electricity, and particularly in the Chapter, wherein we shall treat more specially of the development of electricity by heat, that we shall be enabled to return, when studying it more profoundly, to the phenomenon that we have been pointing out, and which has been the object of the labours of a great number of philosophers. What we have said of it, however, suffices to justify the double assertion that we have put forth above, namely, that the heat liberated by the transmission of dynamic electricity is not due to the reunion of the two electricities, but that it must rather be attributed to a molecular motion, the production of which, or at least the increase, is brought about by this reunion. Therefore we conceive that, in the case of crystallised bodies, in which the molecules are retained by forces that do not allow of their immediately acquiring, under the influence of the current, a

position that places the direction of their natural rotation in harmony with that of the rotation, which the current tends to impress upon them, these two directions may be contrary in such a manner, that the passage of the current counteracts the motion, and that, far from increasing the velocity, it diminishes it, which, according to the present theories upon heat, lowers instead of elevates temperature. It is no longer the same, when the current, becoming more powerful, the molecular forces ought to yield to it, and no longer oppose the particles acquiring the position which it tends to impress upom them, — a position which they occupy without conflict in non-crystallised bodies and in liquids.

These molecular motions, which are so perceptible in the voltaic arc, exist no less in the spark, although they are less sensible in it. We have seen the proof of this in the transport of particles, that is brought about by the electric spark; and in the formation of Priestley's rings. Thus the electric spark, like the arc, is the result of a very rapid motion, impressed upon material particles, and which is accompanied by a powerful heat and light; but its excessively short duration renders the perception of these phenomena much more difficult than in the arc, which is permanent. Is not the light of the spark alone due to the incandescence of the small solid particles, detached from the conductor, and of the ambient gaseous molecules; or rather, might it not in part arise also from a disturbance, impressed directly upon the ether by the motion of the electricity? It would appear to me a difficult matter to admit that electricity might act directly upon the ether, so as to produce in it luminous undulations; for there is no electric light in perfect vacuum, except that which arises from the incandescence of the particles detached from the conductors by the discharge; and this light always manifests itself every where, when there are material particles in a space that contains but few of them. Thus in the long tube, in which perfect vacuum has been made, the electric light is seen to travel along the interior surface of the glass tube, to which air or vapour always remain adhering. I have even succeeded in showing, in a striking manner, the presence of a

ponderable substance, where there is electric light, even in apparently the most perfect vacuum. The following is the description of an experiment, which, although made with a view of explaining auroræ borealeS, as will be seen hereafter, proves well the principle that I have just laid down.

I introduced into a globe of glass 12 or 15 in. in diameter (*fig.* 218.), by one of the two opposite necks with which it is

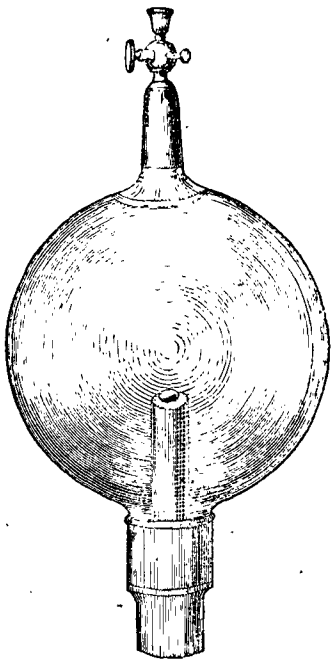

Fig. 218.

furnished, a rod of soft iron about $\frac{3}{4}$ in. in diameter, so that one of its extremities abuts nearly to the centre of the globe, and the other comes out through the tube, and passes beyond it. The iron rod is covered along its whole extent, except at its extremities, with a very thick insulating coat, formed first of gum-lac, then of a glass tube itself covered with gum-lac, then of a second glass tube, and finally of a very smooth coat of wax; the insulating coating should be, in all, $\frac{2}{5}$ in. in thickness, which gives a diameter of about $1\frac{1}{2}$ in. to

the bar thus covered. A ring of copper surrounds the bar above the insulating coating in the portion nearest to the neck, but in the interior of the globe. This ring may be placed in communication with an electric source exterior to the bar, by means of a wire carefully insulated, which traverses the neck and terminates exteriorly by a hook. A stop-cock, fixed to the second neck of the globe, allows of a vacuum to be made in it. When the air is sufficiently rarefied in it, the hook is put into communication with the conductor of an electrical machine, and the exterior extremity of the soft iron rod with the ground, so that the electricity forms in the interior of the globe a luminous brush, more or less irregular, which originates at the ring and abuts upon the upper extremity of the soft iron. But at the moment when the exterior extremity of this iron is placed upon the pole of a powerful electro-magnet, the electric light assumes a very different aspect. Instead of coming out indifferently from different points of the upper surface of the iron cylinder, it comes out equally from all points of the circumference of this surface, so as to form round it, as it were, a continuous luminous ring. This is not all: this ring possesses a rotatory motion around the magnetised cylinder, sometimes in one direction, sometimes in the other, according to the direction of the electric current, and the direction of the magnetisation. Finally, more brilliant jets seem to come out from this luminous circumference, without being confounded with the rest of the brush. As soon as the magnetisation ceases, the luminous phenomenon becomes what it was before, and as it generally is in the experiment known under the name of the electric egg.

Is it not evident that these luminous jets, which obey the action of the magnet, like movable conductors, are, in this case, as well as in that of the voltaic arc, composed of material particles traversed by the discharge? I am disposed to admit that these particles, are gaseous, and that they arise from the film of air remaining adherent, notwithstanding the vacuum at the upper surface of the cylinder of iron, out of which the electric jet comes, that draws them with it so as to

form the brush, which, as we have seen, is composed of small filaments of air. Moreover, the violet light of these gaseous filaments, traversed by the discharge, differs notably from the white and much more vivid light of the solid particles detached from conductors, which are found in a greater or less proportion in the midst of the electric light. There exists, between these two appearances, almost the same difference as is observed between the pale light of the flame of pure hydrogen or of alcohol, and that of this same flame when small particles of carbon, or a thin plate of platinum are introduced into it, which become incandescent.

However, M. Neef, who made a particular study of the electric light, is disposed to think that the light of the bluish colour, which is manifested around conductors charged with electricity, arises from a species of gaseous atmosphere, with which every metal in the solid state is surrounded, and which is rendered visible by the electricity, where it acts with the greatest intensity. The presence of this metallic atmosphere would explain the changes of colour, which the light undergoes, with the nature of the metals, between which the induction spark passes. M. Neef had observed it with zinc, which gives a blue light, and copper, which gives a green one. M. Matteucci made the same observation with points of zinc, copper, and gold. However, M. Neef recognised that, with frictional electricity, which has much more tension, the air and elastic fluids may become luminous, which explains why the different gases produce light of a different colour. It is very probable that it is the same with the light of the induction spark; and that the differences that are presented in its colour, according to the metals between which it is manifested, are due to the mixture of incandescent metallic particles with gaseous particles equally luminous.

We have already spoken in a former paragraph, at p. 277., of the interesting labours of Neef, who was the first to apply successfully the microscope to the study of the luminous phenomena of electricity, by carefully examining, with the assistance of this instrument, all the peculiarities of the induction spark. This philosopher had thought he might be

able to distinguish the two poles, in respect to their calorific and luminous properties, attributing to the positive pole the liberation of heat, the reduction into dust, and the volatisation of the substance of the electrode; and to the negative pole, the production of primary light, namely, of the light that does not arise from an increase of temperature. The existence of this light, which he terms *cold flames*, appears to M. Neef very distinct from that which results from the incandescence and combustion of the solid particles, detached from the electrodes; and he considers it as being of the same nature as phosphoric light, which, in like manner, seems not to be endowed with heat; this light is, therefore, according to him, independent of heat, whilst the secondary light is due to the heat which, arising from the positive pole, produces incandescence and transports to the negative pole particles of the positive electrode, when it acquires a certain degree of intensity; the heat and light are then confounded, but not in their origin. It is by diminishing sufficiently the intensity of the induction spark that we succeed in obtaining light at the negative electrode alone; and for this purpose M. Neef makes use of a small disc and a platinum point, between which he made this spark to pass by means of a similar apparatus to that of *fig.* 149 *, the force of which he might diminish at pleasure.† According as the induction current is in one or the other direction, it is at one time the point, at another time the disc, that is illuminated with a violet light, whilst the opposite electrode remains dark. Riess, as we have seen, has shown that Neef's luminous phenomenon is analogous to that of Faraday's dark discharge; and that it may in like manner be produced by means of a powerful induction current, transmitted in rarefied air between two balls, of which one, the negative, is luminous, and the other, the positive, remains dark. He

* Vol. I. p. 387.

† The most simple means of causing the intensity of the induction current to vary, is to introduce into its circuit a small column of water placed in a tube in which are inserted two metal points, that may be brought more or less near, and so that the course of the current through the water may have more or less length; he called the apparatus a *moderator*.

has shown that with a less rarefaction, the positive pole becomes also luminous, which proves that the liberation of light is not an exclusive property of the negative pole.

Neef's idea of connecting the liberation of light and heat with the nature of the polarity, negative or positive, does not therefore appear to us to have any foundation; the more so as there is no longer any polarity, as soon as there is any discharge or current; and as heat and light are developed, only so long as there is electricity in motion. However, there are two facts well demonstrated: the first, that, as soon as there is transmission of a discharge or an electric current through a bad conductor, the positive electrode suffers an increase of temperature and a mechanical disaggregation, which is not suffered in the same degree by the negative; the second, that the emission of light is not always identical at the two electrodes, and that, according to the circumstances which accompany the transmission of electricity, it is more powerful at the positive, than at the negative electrode. I am disposed to think that these differences are due essentially to the nature of the medium interposed between the electrodes, as well as to the nature and form of the electrodes themselves, which is also the result of experiments made with the voltaic arc. Perhaps also, in certain cases, the chemical alterations, that occur to the medium traversed by the electricity, are not altogether foreign to these effects. But before seeking further for the explanation, let us endeavour to study, better than we have hitherto done, the electric light itself, its special properties and its effects: we shall find in this study a means of investigating its nature better, and of better explaining its various appearances.

Very soon after the discovery of the voltaic arc, it had been remarked that, both in respect to its intensity and to its other properties, this light had much resemblance to solar light. Brande had shown that it determines immediately the combination of chlorine and hydrogen: I had myself observed that a daguerreotype impression might be obtained of a plaster bust, illuminated by this light. I had also proved that it presents no trace of polarisation;

another analogy with the rays of the sun. Subsequently, MM. Fizeau and Foucault, on comparing the two lights, either with each other or with that which is produced by oxygen and hydrogen gas projected upon lime, had confirmed this analogy; for they found that, both in respect to their chemical action upon an iodized daguerreotype plate, as well as in that of their simple luminous action, estimated by the comparison of the images received upon a translucid screen, the intensity of the light of the carbon points, produced by 46 Bunsen's pairs, is to that of solar light as 1 : 4; and even as 1 : 2·5, with three parallel series, namely, with forty-six pairs of triple surface; whilst the intensity of the light of oxygen and hydrogen gas is to that of the voltaic light as 1 : 35 or as 1 : 56, with the 46 pairs having large surface. We therefore see how much nearer the electric light approximates to solar light, than does that which is produced by the combustion of the gaseous mixture. One very remarkable thing is, that we arrive at the same result, both in respect to optical intensities as well as chemical intensities; which proves that these two intensities are in the same relation. I should add that the voltaic light, submitted to experiment, was furnished by the extremity of the positive electrode, which appears to be the most brilliant portion of the arc formed by two carbon points. M. Despretz, in his researches on the voltaic arc, has fairly proved that, if the arc increases in length with the number of pairs, arranged in series, the intensity of its light, having passed a certain limit, does not follow the same progression, but increases with the surface. Thus, beyond 100 pairs the intensity does not sensibly increase, if we augment the number of pairs in series even up to 600, whilst the arc becomes six or seven times longer; but if we arrange the 600 pairs in six parallel series, so as to have 100 pairs of a large surface, then the intensity of the light increases almost proportionately to this surface.

Casselmann, in operating with carbon points, prepared like the carbon of the Bunsen's piles, but which had been plunged in a solution, either of nitrate of strontian or nitric acid, &c., had found that these points produce a light much

more equal and more permanent, than that which had been obtained with pure carbon: only it is differently coloured, according to the nature of the solution, into which the carbon points have been plunged

The following is a Table, which contains the degree of intensity of the light for each arc, with the force of the corresponding current, measured by means of a tangent galvanometer, placed in the same circuit of which the arc forms part. The luminous intensity is compared with that of a stearine taper taken as unity.

	Distance of the Points.	Force of the Current.	Intensity of the Light.
Pure Carbon - - -	·019 in.	95	932
	·176 -	68	139
Carbon plunged into nitrate of strontian - - -	·019 -	120	353
	·265 -	88	274
Carbon plunged into chloride of zinc - - -	·039 -	80	624
	·196 -	67	129
Carbon, with borax in sulphuric acid - - -	·058 -	72	1171
	·196 -	64	145

These results are only approximate, on account of the mobility of the light of the incandescent extremities of the points, that contribute for the most part to the vivid light of the arc. However, compared with others, in which the light had been rendered more steady by means of the action of a magnet, which imparted to it a determinate direction, it is found that the luminous intensity increases in a progression a little more rapid than the force of the current.

M. Masson, who has made a very particular study of the electric light, directed his attention principally to that which is manifested by the spark; he produced it, in his experiments, by the discharges of a condenser, with plates of glass covered on each of their faces with a thin sheet of tin-foil. The instrument intended for these experiments, and which he called an *electric photometer*, is constructed upon the following principles: — A disc of paper, upon which black and white sectors of equal dimensions have been traced, moving with sufficient rapidity, appears of a uniform and greyish tint, if it is

illuminated with a permanent white light. This well-known phenomenon is due to the persistence of the sensation. When, instead of a fixed light, we employ an instantaneous light for illuminating the sectors, the disc appears as if it were fixed, the sectors not having been able sensibly to change place during the existence of the light. The eye in this case perceiving, and with great distinctness, all the details of the disc, we already acquire a notion of its extreme sensibility, and of the rapidity with which the perception of objects is exercised, and our judgment of their nature is formed. If the disc, illuminated by a permanent light, is suddenly illuminated by an instantaneous light, an electric spark, for example, we shall see the sectors appear again, for a certain intensity of this latter. If the instantaneous light is successively reduced, a period arrives when the sectors will disappear and the disc will appear illuminated of a uniform tint. In this case, the instantaneous light is a fraction of the permanent light, variable with the eye of the operator, but invariable for the same eye, the circumstances of vision remaining the same. In fact, on account of the persistence of the sensation, the place, that a black sector occupies not reflecting the light of the spark, has entirely preserved the primitive illumination; that which is occupied by a white sector, sends to the eye as much light as the former, plus the light due to the spark. When the intensity of this latter shall represent the limit of sensibility of the eye of the observer, the disc will appear uniformly illuminated. The relation between the intensities of the illuminations of the black and white sectors at the moment when they cease to be distinguishable, may vary, as we shall see further on, from $\frac{1}{30}$ to $\frac{1}{120}$, according to the sensibility of the eye of the observer. With regard to the relation between the intensity of the light of the spark and that of the fixed light, it depends upon the dimensions of the black and white sectors. If the sectors are equal, — and it is the case in these experiments, — the relation between the instantaneous and the fixed light is the half of that found by experiment. In fact, let us suppose that the sensibility of the eye is $\frac{1}{60}$; when the sectors dis-

appears the relation between the electric light and the fixed light is only $\frac{1}{120}$ of the illumination that would be produced by the fixed light upon a perfectly white disc; because the disc in motion sends to us only the half of the light, that it would reflect if it were in a state of rest and perfectly white. The intensity of the electric light, given by experiment, would be only $\frac{1}{180}$ of the fixed light, if the black surface were two-thirds of the white surface.

The apparatus necessary to the experiments are an electric machine, condensers, a micrometer for measuring the explosive distances of the spark, conductors of peculiar form and nature, the apparatus intended to contain the permanent light, and finally the photometer. The condensers are flat and formed of plates of glass, covered on each of their faces with a thin sheet of tin-foil, which enables us easily to measure their surface and their thickness, and to estimate their degree of homogeneity. The fixed light is produced by a very good Carcel lamp, the illuminating power of which may be rendered constant for two or three hours. The lamp (*fig.* 219.) is contained within a wooden box blackened, similar to that of a phantasmagoria; and this system is movable upon a grooved road furnished with a division in millimetres ($\frac{1}{25}$ in.), which, by means of a vertical point cor-

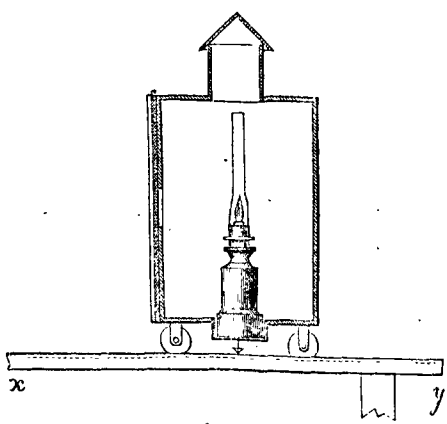

Fig. 219.

responding with the centre of the flame, measures its distance from the illuminated disc. The photometric apparatus is essentially constituted of a disc of thick paper (*fig.* 220.) 3 in. in diameter, upon which have been traced sixty sectors, alternately black and white, and of the same dimensions; the disc is cemented upon a copper support, fixed by a socket to the principal axis of a clock-movement, contained in a box; by the aid of a detent, we are enabled to arrest or to set in motion the disc, the velocity of which can attain to a maximum of from 200 to 250 turns per second.

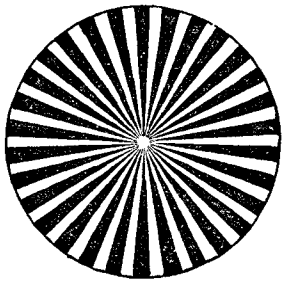

Fig. 220.

The apparatus complete is represented in vertical projection

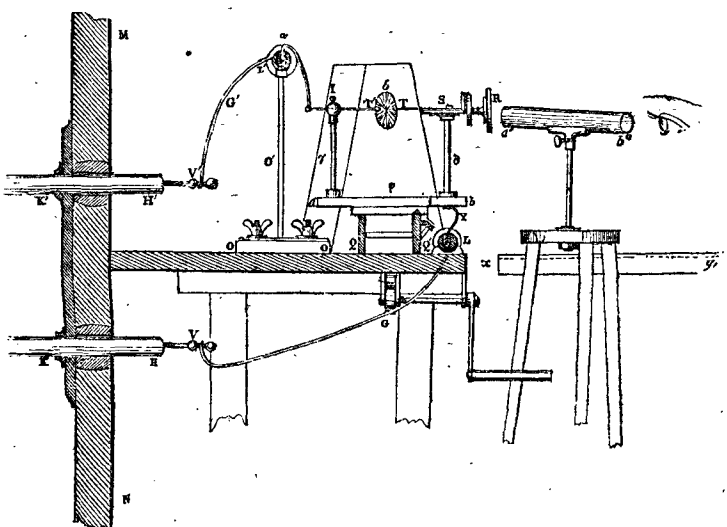

Fig. 221.

(*fig.* 221.); M N, is the partition that separates the dark room, in which the apparatus is placed, from the room, in which are the electrical machine and the condenser, the discharge of which arrives by the brass conductors V and V′, sustained in

the centre of glass tubes K H, and K′ H′, by corks covered with an insulating coating. The armatures of the condensers communicate by metal conductors, V G and V′ G′, with columns of mercury, contained in grooves, L L and L′ L′, hollowed in wooden cylinders and varnished within side with black sealing-wax. These conductors, like all the others attached to the apparatus placed in the dark apartment, are covered with varnish of dead black, so as to avoid all reflection. The rods V G, and V′ G′, amalgamated on all the points that plunge into the mercury, abut at opposite extremities of the canals L L, L′ L′, *so that the circuit traversed by the current remains constant.* The cylinder L′ L′ is insulated upon glass legs, covered with a coat of blackened gum-lac; L L is fixed to the support that receives the apparatus from which the spark passes. This wooden support, constructed like the fixed piece of a planing machine, is marked by the letters Q Q; it is placed upon a table, firmly fixed to the wall or to the floor; it carries on one of its faces a division in millimetres, which is not visible, because it is traced upon a horizontal rod, and perpendicular to the plane of the figure. The apparatus, that is the seat of the spark, is movable upon Q Q, and may be brought, by means of a Vaucansin endless chain and a handle, to different distances from the photometer. The piece carrying the spark is composed of a plank *a*, *b*, supporting two vertical rods, one of glass, *a* γ, the other of copper, *b* δ. At I is invariably fixed, by a binding screw, a metal conductor, plunging at ω into the mercury; this conductor is terminated at T′ by a ball screwed on. Another conductor, T S, carrying also a ball, T, screwed to it, is set in motion by means of a micrometer screw, R S, giving half a millimetre ($\frac{1}{50}$ in.) The communication with the ground is established by the conductor, δ *b*, Y, L, of which the part Y, L, plunges into the groove of mercury L L. The supports, *o o*, fixed upon the table by binding screws, carry a groove, which enables us to establish parallelism between the trenches L and L′. The centre of the disc, that of the flame of the lamp, and the spark, are contained in a same horizontal plane. The eye of the observer looks at the disc through a tube, blackened in-

teriorly and exteriorly, having its axis perpendicular to the plane of the disc; this tube contains diaphragms, which allow of the eye seeing the sectors alone. The Carcel lamp, with its box, is placed behind the eye of the observer, so as to illuminate the disc upon the horizontal support, when the box that contains it, moves along the division.

After various preliminary essays, which proved to him the accuracy and the sensibility of his apparatus, M. Masson found that the intensity of the electric light, produced by discharges, depended upon the following elements: 1st, the distance of the explosion; 2nd, the surface of the condensers; 3rd, the thickness of the condensers; 4th, the nature, and consequently the condensing power, of the condensers; 5th, the conductibility of the circuit; 6th, the nature of the medium in which the explosion is produced; 7th, the nature of the poles, or electrodes, between which the spark passes. He established, moreover, the following laws: —

First Law. *The intensity of the electric light varies in the inverse ratio of the square of the distances of this light from the surfaces illuminated.*

Second Law. *The intensity of the electric light varies proportionately to the surfaces of the condensers, and in the inverse ratio of their thickness.*

Third Law. *The intensity of the electric light increases proportionately to the squares of the distances of the explosion.*

These are general laws, and independent of the other elements, which influence only the absolute intensity of the electric light. It is very remarkable that, upon comparing the results of M. Masson with those of Riess, we find that the same laws regulate the development of light and that of heat, in such sort that the same formulæ are applicable to them; and that we may lay down as a principle, that *the quantities of heat are proportional to the quantities of light.*

We cannot here introduce all the details of the numerous experiments, by means of which M. Masson has obtained the laws that we have just laid down, any more than those which he has made in order to study the influence of the conductibility

of the circuit, and the explosive distance of the different gaseous and liquid substances.* We shall confine ourselves to transcribing two of the Tables, that contain the results relating to the influence exercised over the intensity of the electric light, by the nature of the electrodes, which will at the same time give the idea of the manner in which this skilful French philosopher operated in his researches.

He employed successively for electrodes, balls of metal of different natures, being about ·15 in. in diameter; at each change of metal, the position of the vernier, corresponding to the contact of the spheres, was determined by bringing the balls towards each other, until a small spark, produced by the electric machine, was seen to disappear between them; then designating the explosive distance by X, that of the spark from the photometer by Y, and that of the lamp by Z, the results are obtained that are contained in the two following Tables; the first of which gives X, Z and Y, being constants, and the second Y, X and Z being constants. In the two series of experiments, the surface of the condenser was 70½ square feet.

Z = 21·22 in. Y = 24·91 in.

Metals.	X.			Mean.
Iron - -	·2141 in.	·2161 in.	·2161 in.	·2154 in.
Copper -	·2078	·2059	·2082	·2073
Brass -	·2067	·2043	·2035	·2048
Tin - -	·1917	·1925	·1921	·1921
Zinc - -	·1921	·1909	·1913	·1914
Lead -	·1650	·1623	·1419	·1630

Z = 21·22 in. X = ·236 in.

Metals.	Y.			Mean.
Copper -	·2959 in.	·2955 in.	·2955 in.	·2956 in.
Brass -	·2971	·2975	·2971	·2972
Iron - -	·3002	·2982	·2990	·2962
Tin - -	·3073	·3081	·3077	·3077
Lead -	·3120	3140	·3128	·3129
Zinc - -	·3136	·3128	·3132	·3132

* We have already treated upon this point in Chapter I. p. 156. *et seq.*

In classing the metals, according to the increase which they are able to produce in the intensity of the spark, we obtain the following order:

First Table.	Second Table.
Iron.	Copper.
Copper.	Brass.
Brass.	Iron.
Tin.	Tin.
Zinc.	Lead.
Lead.	Zinc.

We see from this classification, that the metals form two distinct groups, between which there exists a very notable difference of action, whilst it is very slight between the metals of the same group. These groups comprise: the one copper, iron, and brass; and the other, tin, zinc, and lead. Now, this classification is the same as that which would have been obtained, by taking into account the tenacity of these metals; those which possess the least tenacity giving a more vivid light than those which possess more. As, on the other hand, the inspection with a lens of the balls that have been used for the production of numerous sparks, shows that they are deeply altered at the points of explosion, especially those of tin, zinc, and lead, we are forcibly led to recognise that the luminous phenomenon is due to the effects of tearing away, which vary with the tenacity of the metals and not with their fusibility; since metals having very different points of fusion present the same intensity to the photometer.* Moreover this order is also that which M. Matteucci had found, by classifying the metals according to the conductibility of the arc to which they give rise. Experiments made successively with brass balls, whose surfaces were smooth or rough, tinned or amalgamated, in demonstrating that it is the surface of the metal, and not its conductibility proper, that exercises an influence over the intensity of the light, confirm that this intensity increases

* M. Riess had already shown that the effect of pulverisation, which the metals equally undergo by discharges, does not depend upon a fusion, but is the direct result of a molecular disaggregation, brought about by the passage of the electricity, which must necessarily, under the same circumstances, vary with the tenacity.

when the metals are easily transported by the discharge. But it is also possible, as we shall shortly see, that the nature itself of the particles transported, contributes its part to the effect observed.

This influence of the nature of the particles is especially sensible, when we study the spectra formed by the passage through a prism of the light of electric sparks. Wollaston, and especially Frauenhofer, had already found that the spectrum of the electric light differs from that of other artificial lights, and from solar light, by the presence of many very clear rays, of which one in particular, which is situated in the green, is of a clearness almost brilliant in comparison with the rest of the spectrum. Mr. Wheatstone having studied the phenomenon, by employing different metals for electrodes, had remarked that the brilliant rays differ in number and in position, according to the metal employed; and that, when the spark occurs between balls of different metals, or made of different alloys, the brilliant rays belonging to each of the two metals are seen simultaneously. The learned English philosopher had operated with the electric light produced either by piles, by induction machines, or by ordinary electrical machines. M. Despretz and M. Foucault have recently made a more complete examination of the spectrum of the voltaic arc. The former has found that the brilliant rays of the arc, produced between two carbon points, are fixed, and independent of the intensity of the current; for he satisfied himself that, on passing from 100 elements to 600, arranged either consecutively or in parallel series of 100, a yellow or blue ray brought into coincidence with the wire of the telescope remains perfectly in the same place. The latter philosopher, M. Foucault, having observed, in this same spectrum, a double line situated at the limit of yellow and orange, recalling to mind, by its form and its situation, the ray D of the solar spectrum, wished to know whether it corresponded with it, and for this purpose he caused a solar image, formed by a converging lens, to fall upon the arc itself, which enabled him to observe, superposed upon each other, the electric and the solar spectra: he thus satisfied himself that the double

brilliant line of the arc did coincide with the double black line of the solar light. This ray D is found in arcs formed by other matters; and when we employ as electrodes metals which do not cause it to appear without difficulty, such as iron and copper, it may be made to revive with great intensity by touching them with potassium or sodium. By making the spectra of different arcs concur with that of solar light, we find that the rays possess all the shades, that are assigned to them by their refrangibility; but what is most striking is, that among these rays, there are some that possess an absolute intensity, enormously superior to that of the corresponding solar ray. Thus, in the arc of the silver, a green ray is found of a dazzling brilliancy, a veritable source of simple light, and which may be rendered as intense as may be desired.

The philosopher, who studied with the greatest care and in the most complete manner, the spectra of electric light, is also M. Masson, who employed for this study both the light of the spark produced by the discharge of condensers, as well as that of the voltaic arc. He found in the spectrum of the electric spark, developed in the air, all the colours of the solar spectrum *, and he found that the brilliant rays by which it is marked, are quite of the same colour as the part of the spectrum of the same refrangibility; although sometimes, when they have too much brilliancy, they appear like white light upon a coloured ground. Moreover, by increasing the intensity of the spark, the rays are rendered decidedly more brilliant and vivid, but neither their position nor their number is changed, as M. Despretz, and M. Foucault had already remarked, for the rays of the spectrum of the arc. We are also able, by an increase of intensity, to extend the violet, which is always the most feeble in the spectrum of the electric light, but we are never able to extend the spectrum on the side of the red; a property similar to that which had been recognised by M. Matthiessen, in the spectrum

* He also proved, as I had already done, but in a more complete manner, that the light of the arc itself never presents any trace of polarisation.

of solar light, to which, as we see, both by this example, as well as by that which precedes, the electric light has a great resemblance.

The most important part of the researches of M. Masson is that which concerns the modifications that occur in the distribution of the rays, when the nature of the metals, between which the spark passes, is changed. He has proved that these rays differ in number and in intensity; but that there are, nevertheless, a certain number of *common rays*, that is to say, rays that remain the same in all spectra, which indicates the measure of their deviation, which is every where similar, whilst the deviations of the others are very different. The values of these deviations have been carefully determined by M. Masson, for a very great number of rays in spectra produced by the spark, in cases where the electrodes were made of the following substances: *carbon, cadmium, antimony, bismuth, lead, tin, iron, and copper.* These numbers may some day, perhaps, serve to establish the proper function of the nature of the particles in the production of the light; for the present, they demonstrate, by the simple fact that they differ from each other, the existence of the function. We shall not refer to them here, we shall content ourselves with a few remarks. Carbon (*fig.* 222.) gives in the violet many very brilliant, but very fine rays; at the end of the violet, they are separated by intervals absolutely dark, considering the feebleness of the light. Cadmium (*fig.* 223.) is, of all the metals tried, the one that gives the most beautiful and the best defined spectrum; it is especially remarkable by very brilliant green and blue rays. The spectrum of antimony (*fig.* 224.) is marked by a multitude of very brilliant rays, much more numerous than in the spectrum of the other metals. That of zinc (*fig.* 225.) contains a very characteristic apple-green; it is very curious that it differs so much from that of cadmium. Copper gives a spectrum remarkable for the number of fine and brilliant rays of blue and violet; those of tin and of iron, of bismuth and of lead, present nothing in particular, except the extent of the violet, and the number of very confused rays that are included in that colour.

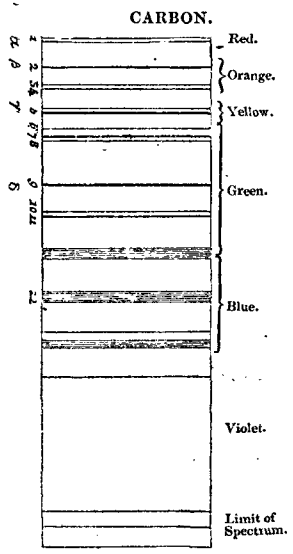

Fig. 222.

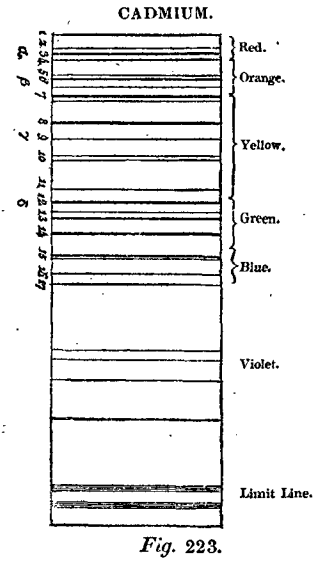

Fig. 223.

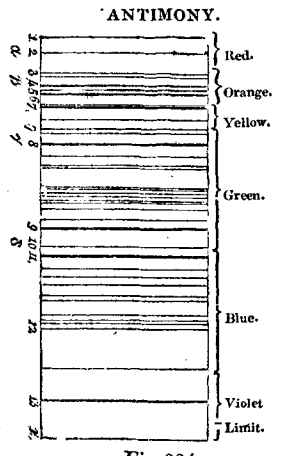

Fig. 224.

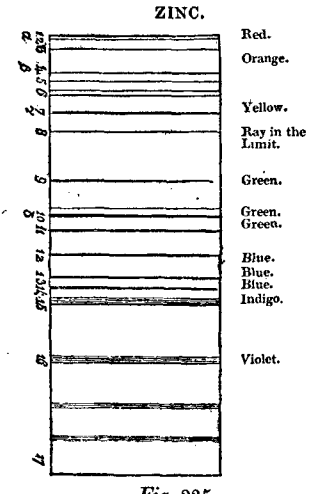

Fig. 225.

Instead of the spark, we may employ as electric light, that which is produced in the voltaic arc; and we obtain with electrodes of different natures spectra perfectly similar to those given by the spark in each case. If the pile that is

employed is tolerably strong (50 to 100 pairs of Bunsen's) magnificent spectra are obtained, which are projected upon screens, like the solar spectrum, which they rival in brilliancy. Only, in order to make these experiments, a fixidity must be given to the light of the voltaic arc, which it does not possess naturally. With this view, we employ an apparatus which, by means of the combination of a mechanical force and of the attraction exercised by an electro-magnet upon a piece of soft iron, connected with the system, brings towards each other the points which are employed as electrodes, as soon as they are too far apart for the arc to be enabled to be established between them, without however allowing them to come into contact, which would cause it to disappear.

Many philosophers have devised and constructed apparatus founded upon this principle: in the list of these apparatus, that of M. Duboscq appears to us one of the most satisfactory; it is essentially intended to produce the arc between two carbon points; but it is equally well adapted to the production of arcs obtained from electrodes of any nature.

The following is a brief description of it. (*Fig.* 226.) The two carbons, between which the light is developed, burn in contact with the air, and shorten at each instant; a mechanism is consequently necessary, which brings them near to each other, proportionally to the progress of the combustion; and, since the positive carbon suffers a more rapid consumption than the negative, it must travel more rapidly in face of this latter; and this in a relation, which varies with the thickness and the nature of the carbon. The mechanism must satisfy all these exigencies. The two carbons are unceasingly solicited towards each other; the lower carbon by a spiral spring, that causes it to rise, and the upper carbon by its weight, which causes it to descend. The same axis is common to them.

The galvanic current is produced by a Bunsen's pile, of from 40 to 50 elements; it arrives at the two carbons, as in apparatus already known, passing through a hollow electro-magnet, concealed in the column of the instrument. When the two carbons are in contact, the circuit is closed, the

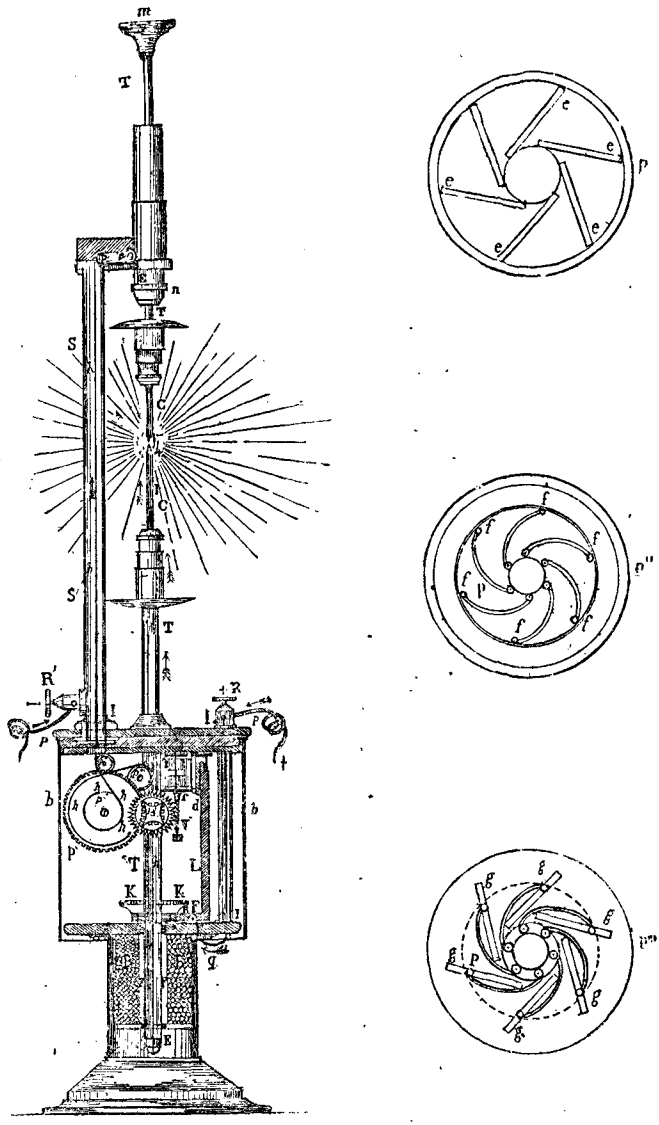

Fig. 226.

electro-magnet attracts a soft iron, placed at the extremity of a lever, which is in gear with an endless screw. An antago-

nist spring tends always to unwind the screw, as soon as a separation is produced between the two carbons; if it is a little considerable, the current no longer passes, the action of the spring again becomes predominant, the screw is unwound and the carbons approach each other, until the current, again commencing to pass between the two carbons, the motion that drew them toward each other, is relaxed in proportion to the return of the predominance of the electricity over the spring; the combustion of the carbons, again increases their distance, and with it the superior action of the spring: hence follows again the predominance of the spring, and so on. These are alternatives of action and reaction, in which at one time the spring, at another time the electricity, has the predominance. On an axis, common to the two carbons, are two pullies; one, the diameter of which may be varied at pleasure, communicates by a cord with the rod that carries the lower carbon, which corresponds with the positive pole of the pile; the other, of invariable diameter, is in connection with the upper or negative carbon. The diameter of the pulley, capable of varying proportionately to the using of the carbon, with which it is in communication, may be increased from 3 to 5. The object of this arrangement is to preserve the luminous point at a convenient level, whatever may be the thickness or the nature of the carbons. It is only necessary to know that at each change of kind or volume of the carbon, the diameter of the pulley must be made to vary. This variation results from that of a movable drum, communicating with six levers, articulated near the centre of the sphere; the movable extremity of the six arms of the lever carries a small pin, which slides in cylindrical slits. These slits are oblique in respect of the sphere; they form inclined planes. A spiral spring always rests upon the extremity of the levers; so that, if the inclined planes are turned towards the right, the six levers bend towards the centre, and diminish the diameter. If, on the contrary, they are turned towards the left, the diameter increases, and with it the velocity of the translation of the carbon, which communicates with the pulley (*vide* P′, P″, and P‴, *fig.* 226.). We may notice, in passing, that this

apparatus is marvellously adapted to the production of all the experiments of optics, even the most delicate; and that, in this respect, it advantageously supplies the place of solar light. We shall moreover have occasion to speak of it again, when we are occupied with the applications of electricity, and in particular of illumination.

In the experiments made with the voltaic arc, the spectrum presents no brilliant ray, when the light emanates from the solid part of the carbon in incandescence. This result is in accordance with what is obtained, upon heating to redness a platinum wire, the spectrum of which, in like manner, presents no brilliant ray.* Neither do we notice any in the spectra arising from the light of a voltaic arc, produced between two charcoal points, plunged either in pure water, or in essence of turpentine, or in alcohol; but if we take for electrodes in alcohol, balls of brass, instead of carbon points, the spectrum presents magnificent brilliant rays; we then remark that the metal has been melted, since the third part of the balls has disappeared, and the liquid has become filled with a black matter, which is probably very finely divided oxide of the metal; whilst, when the electrodes are of carbon, the liquid retains its transparency, which proves that there has been no transport of particles; whence it follows that there were no rays. This absence of transport is very sensible in alcohol, in which the same luminous intensity may be obtained for a long time, by preserving the same distance to the carbons. We may add that the spectrum of the light, arising from the electric sparks produced in liquids, in like manner presents no brilliant rays; perhaps, with more powerful discharges, which might produce a transport of the matter of the electrodes, some might be obtained.

It would be very interesting to study the influence exercised over the spectrum of the light of the electric spark by a change in the nature or in the density of the gaseous medium, in which it is produced,—an influence which, as we

* This absence of rays in this case, proved by M. Masson, resulted already implicitly from Mr. Draper's very interesting researches upon the luminous and calorific intensities of a platinum wire heated progressively by the current.

have seen, is so great over the form and the colour of this spark. M. Masson, who has also made some experiments upon this particular point, has found that the rarefaction of the air diminishes the intensity of the colours, so as almost to make them disappear; but that it, in no way, changes, either their number, or the position of the brilliant rays, which appear more feeble, it is true, upon a ground absolutely dark.

In hydrogen, the spectrum of the spark presents the same appearances as in rarefied air. The colours of the spectrum are not distinguishable; and, upon a dark ground, are perceived very feeble brilliant rays. We know that the spark itself in hydrogen possesses a very feeble reddish purple light, absolutely similar to that which is obtained in rarefied air. However, if we desire to obtain the spark in hydrogen, we require, for the same explosive distance, the same quantity of electricity as in air under the same pressure; and the discharge has the same intensity in both cases. The difference in the two lights, which causes that of hydrogen to become similar to that of rarefied air, can therefore be only due to the molecules of hydrogen giving a less vivid light than those of air under the action of the same discharge; and to the particles detached from the electrode suffering a less powerful incandescence in the former gas than in the latter.*

The detailed study that we have been making of the electric light, confirms all that we have said on the mode of the propagation of electricity, in stating that it could only occur by the intervention of ponderable matter. Masson indeed satisfied himself that the barometric vacuum cannot conduct a current or a discharge, unless the tension of the electricity is considerable, namely, is sufficient to detach some minutely divided particles from the electrodes. With regard to the light, it is produced by a current or a discharge which, propagating itself by the intervention of ponderable matter, heats it in the same manner and

* There are evidently particles detached in hydrogen, as in rarefied air, since the spectrum presents rays as well in the one as in the other.

according to the same laws as a voltaic current heats wires and renders them luminous. The state of bodies (solid, liquid, or gaseous) in no way modifies, the general laws of electro-dynamic action: Savary had already demonstrated this, in obtaining exactly the same degree of magnetisation for steel needles, placed some above a tube, in which Boyle's vacuum had been made, others above a metal conductor of the same diameter as the tube, each forming part of the same circuit traversed by a discharge.

With regard to the light itself, it always possesses the same properties, whatever be the means employed for producing it; and all the phenomena, that we have been studying, confirm us in the opinion that it really arises from the incandescence of the particles of the medium, which is traversed by the discharge or the electric current, and from that of the particles, which are detached from the electrodes, the presence of which determines the rays of the spectrum, that vary with their nature. It would be interesting to study with care the heat, that accompanies this light, in the various cases, in which it is produced. We have seen that, in the case of the voltaic arc, wherein the transport of incandescent particles is considerable and continuous, the temperature is very elevated. But, when the spark is in question, E. Becquerel has demonstrated that the radiant heat is null or very feeble, which is for the most part due to its shortness of duration; for we know that it has nevertheless a calorific power sufficiently great to determine the combination of the gases,—hydrogen and oxygen, for example—when it is transmitted between two platinum points in a endiometer, filled with a detonating mixture. But, even in this case, it is necessary that the discharge be sufficiently powerful to detach and to carry along particles from the metal points between which it takes place, as is indicated by the vivid and white light of the spark, and as is proved by the condition of the points, when they have been for some time employed in the experiments. Otherwise, the simple lights, that result from the mere incandescence of the gaseous medium do not liberate any sensible radiant heat, although,

with very delicate apparatus, we ought necessarily to detect a little.

The electric light enjoys one other remarkable property, namely, that of exciting phosphorescence in bodies that are susceptible of it. This property is independent of that possessed by the discharge of producing the same effect. Indeed, if we introduce fragments of calcined oyster-shells into small glass tubes, hermetically sealed, and themselves placed in other larger tubes, and pass a great number of electric discharges over the exterior surface of these tubes, the fragments become phosphorescent on their being heated; the light of the voltaic arc produces the same phenomenon, but in a less degree. Its effect is due to the electric light, and not to the direct influence of the electricity; since on enclosing the same phosphoric substance within tubes of red, yellow and deep blue glass, Seebeck has remarked that at the moment when the three tubes are exposed to the light of the discharge, it is only the substance in the blue tube that becomes luminous; which proves that the blue glass is the one that allows those of the phosphogenic rays of electric light to pass, as it allows those of solar light to pass. MM. Becquerel and Biot have made a very great number of experiments, in order to study the influence of different screens over the transmission of radiation, arising from the spark that produces phosphorescence, and they have found that it was very distinct from luminous radiation. It is the same with the phosphorescence produced by solar rays; and of these, the rays that produce it are the most refrangible of the spectrum, whilst the others, such as the red rays, not only do not produce, but they even destroy it. The phosphogenic rays of solar light, and those of electric light, are therefore very nearly the same, and probably also the same as the chemical rays. The phosphogenic property of electric light is therefore entirely connected with its chemical property, which we have already proved; and we must in no way confound it with the property possessed by electricity when acting directly upon bodies, of rendering them phosphorescent, or of disturbing their chemical state.

Moreover, the light of phosphorescent bodies has so great a relation, in its different tints and in its intensity, to the light which is in certain cases developed by electricity, that it is very difficult not to impute to it an identity of origin. Phosphorescence is therefore very probably a light resulting from small electric discharges, which are brought about through the air adhering to the surface of bodies, that are endowed with this property; and what renders this hypothesis more probable is that, besides the similitude of appearance, we observe that all the means and all the circumstances that produce and favour the development of phosphorescence, are the same that produce and favour the liberation of electricity, as we shall have occasion to see, when we shall be studying the sources of electricity; and it is especially that the process most suited for rendering bodies phosphorescent, is to let them be traversed by an electric discharge; and consequently to impart to them directly that electricity, which the other processes develope in them only indirectly.

To sum up, we may conclude from all the facts that we have explained in this Chapter,— 1st. That the production of electric heat and light cannot take place without the establishment of a closed circuit, all the parts of which exercise the same exterior electro-dynamic action, conformably with Ohm's laws; — 2nd, that this production takes place in the points of the circuit, where the electricity in motion (whether discharge or current) experiences the greatest resistance; — 3rd, that the parts of the conductors, which limit the portions of the circuit, where the resistance is greatest, and where consequently the heat and light arise, undergo calorific, luminous, and molecular modifications, which depend at the same time upon their proper nature, and upon that of the electricity, (positive or negative,) of which they are the electrodes: — 4th, that these modifications seem to indicate that the movement of rotation of the particles, whose acceleration, produced by the transmission of electricity, is the probable cause of electric light and heat, is influenced either by the nature itself of the substances, or by the direction of the discharge or of the current; which determine, in the

case of the spark and of the arc, a movement of transmission over and above that of rotation.*

* *List of the principal works relating to the subjects treated upon in this Chapter.*

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Van Marum.—Idem. *Bibl. Brit.* t. lvi. p. 210.

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Joule.—Laws of heating by currents. *Arch. de l'Elect.* t. ii. p. 54. and t. iv. p. 483.

E. Becquerel.—Idem. *Ann. de Chim. et de Phys.* (N. S.) t. ix. p. 21. Phosphorescence and radiation of the spark *Bibl. Univ.* t. xx. p. 344. and 394.

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Robinson.—Influence of the medium upon the heating. *Trans. of the Irish Academy*, vol. xxii. (Part I.) p. 3.

Grove.—Idem. *Arch. des Sc. Phys.* t. ix. p. 140. and t. xii. p. 165. Incandescence and deflagration. *Bibl. Univ.* (1839) t. v. p. 18. and 122.; t. xxv. p. 426. and t. xxix. p. 387.

Clausius.—Idem. *Arch. des Sc. Phys.* t. xxii. p. 269.

Favre.—Heat liberated in the pile. *Ann. de Chim. et de Phys.* (N. S.) t. xl. p. 393.

Faraday.—Light and appearance of the spark. *Phil. Trans. Collection of Memoirs*, and *Bibl. Univ.* t. xvii. p. 178.

Quet.—Stratification of the induction spark. *Comptes rendus de l'Académie des Sc.* t. xxxv. p. 949. Influence of the magnet upon the voltaic arc. Idem.

Neef.—Electric light and heat. *Arch. des Sc. Phys.* t. i. p. 30., and t. iii. p. 391.

Marianini.—Sparks in liquids. *Bibl. Univ.* (1843), t. xlvii. p. 253.

Sillimann.—Voltaic arc. *Ann. de Chim. et de Phys.* t. xxiv. p. 216.

Despretz.—Voltaic arc. *Comptes rendus de l'Acad. des Sci.* t. xxx. p. 367., and t. xxxi. p. 418. Formation of the diamond. *Compte rendu de l'Acad. des Sc.* t. xxxvii. (5th and 19th Sept. 1853.)

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Gassiot.—Heating of the positive wire. *Bibl. Univ.* t. xviii. p. 369.

Fizeau and Foucault.—Electric light. *Arch. de l'Electr.* t. iv. p. 311.

Foucault.—Idem. *Arch. des Sc. Phys.* t. x. p. 222.

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Wheatstone.—Rays of the electric spectrum. *Traité de Phys. de Beoquerel*, t. ii. p. 127.

Duboscq.—Electric regulator. *Comptes rendus de l'Acad. de Sc.* t. xxxi. p. 807.

Becquerel.—Electric heat and light; phosphorescence. *Traité de l'Electricité* and *Traité de Physique.*

Draper.—Light of an incandescent platinum wire. *Phil. Mag.* vol. xxx. p. 345. (1847).

Viard.—Heat in wires by the current. *C. R. de l'Acad. des Sc.* t. xxxix. p. 904.*

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* M. Viard has verified directly by experiment the explanation given by Clausius of the effect of the ambient medium upon the heat developed by the current in wires. He has shown, by the introduction of a rheostat into the circuit, that the heat developed is always proportional to the real resistance that exists, at the moment of the passage of the current, as Mr. Robinson had already proved (p. 242.); so that the presence of a less cooling gas, by increasing the resistance of the wire that it surrounds, causes the current to develope in it more heat. But if, upon shortening the wire of the rheostat, the resistance is rendered equal to what it was when the wire was surrounded with the more cooling gas, then the quantity of heat liberated by the current, is the same as it was in this latter case.

CHAP. III.

CHEMICAL EFFECTS OF DYNAMIC ELECTRICITY.

Decompositions brought about by the Voltaic Current.

NICHOLSON and Carlisle, a short time after Volta had constructed his pile, succeeded in decomposing water, by plunging into it two wires, of which one was in communication with the positive pole, and the other with the negative pole. The two wires were of brass; the one that was in communication with the + pole gave off no gas, but underwent oxidation, whilst the one that was in communication with the − pole liberated hydrogen. The production of the gas was the more abundant, in proportion as the two wires were nearer together. These observers remarked besides, that the decomposition of water not only takes place between the two poles of the pile, but also between the metals of two consecutive pairs, separated by the humid conductor. Finally, they succeeded as easily in obtaining oxygen as hydrogen, by substituting platinum wires for the copper wires, that established communication between the water and the poles of the pile. The two gases may be collected separately, if the precaution be taken of placing over each wire a tube filled with water, at the top of which the gas that is liberated, naturally arranges itself; it is necessary that the two tubes should not touch the bottom of the vessel, in order that the two wires may really be plunged into the same water.*

Cruikshanks was the first who obtained an effect by plunging into separate vessels each of the poles of the pile, which were silver wires, and uniting at the same time the

* See Vol. I. p. 31. *fig.* 18.

two vessels by another silver wire; he perceived hydrogen to be liberated from the wire, that was in communication with the — pole of the pile, whilst the end of the wire, that was plunged in the same vessel, was attacked. The other end of this same wire, which was plunged into the second vessel, liberated hydrogen; and finally, the wire, that was in communication with the + pole, was attacked. The same philosopher, having plunged two silver wires into a diluted solution of nitrate of silver in ammonia, obtained at the negative wire, first an abundant production of gas, then filaments, which were recognised as being metallic silver. The silver wire, that was in communication with the positive pole, gave forth little or no gas, seeing that it was attacked. With copper wires, plunging in an ammoniacal solution of copper, Cruikshanks obtained metallic copper around the negative wire: the liquid lost its colour and became similar to distilled water, the copper having been all precipitated.

Without dwelling upon other of Cruikshanks's experiments, of the same kind, nor upon that of Henry on the decomposition of ammonia, we will add that Davy obtained similar results, but upon a greater scale, with a pile of 110 pairs, which enabled him to prove that if, instead of connecting by a wire the vessels full of water, into which are plunged two gold wires, that communicate respectively with the poles of the pile, communication is established by a piece of fresh muscle or by a vegetable fibre, the gases are liberated at the end of the polar wires, hydrogen at the negative wire, and oxygen at the positive. It is the same if the communication between the vessels is established by the intervention of the human body, which can easily be done by plunging into them a finger of each hand. There is no gaseous liberation at the extremities of the fibre or of the fingers, that are immersed in the water of the respective vessels, as there is when it is a wire by which they are connected. Davy further remarked, that if, by means of muscular fibres, the respective poles of the pile are made to communicate with a vessel filled with water, and the two vessels are connected together

by a silver wire, a liberation of hydrogen is obtained at the extremity of the wire, that is plunged into the positive vessel, and an oxidation at the extremity, that is plunged into the negative vessel.

In all these experiments, the gases oxygen and hydrogen are not always quite pure; but they are more or less mixed with the nitrogen that arises from the atmospheric air dissolved in the water; however, by taking many precautions, and employing only wires that are not susceptible of oxidation, such as gold wires, Davy found that the gases oxygen and hydrogen were truly liberated in the proportion that constitutes water.

Many philosophers had thought they perceived the formation of new bodies; and in particular that of a peculiar acid in the action of the pile upon certain liquids; but Davy, taking up anew the entire subject, succeeded, after a series of laborious researches, in establishing, upon perfectly sound bases, the true chemical power of voltaic electricity. He was desirous, above all, to prove that, in electro-chemical decompositions, there were never any other elements liberated at each of the poles, than those contained in the bodies, submitted to the action of the voltaic electricity. Upon operating with vessels of various substances, agate, wax, Carrara marble and glass, he clearly found alkalies at the negative and acids at the positive pole; but he satisfied himself that these acids and alkalies were derived from the substances themselves of the vessels, which the water was enabled to dissolve, especially under the influence of electricity. It might even be seen, when much soda had been obtained in a vessel of glass, that the latter had been strongly attacked, at its point of contact with the wire. Having yet observed traces of acid and of alkali with gold vessels, Davy satisfied himself that these elements were derived from a small quantity of salt, remaining in solution even in distilled water; and having succeeded in perfectly depriving this water of it, there was no longer any trace of acid or of alkali; except in some cases, where there was a little ammonia at the negative pole and nitric acid at the positive, the formation

of which was evidently due to the combination of hydrogen and oxygen, in the nascent state, with the nitrogen, dissolved in the water. Indeed, on placing the water, submitted to decomposition, in vacuo, and still better in hydrogen, there was no longer at the two poles anything besides perfectly pure oxygen and hydrogen.

Thus it is well established that dynamic electricity, acting upon bodies susceptible of being decomposed, *produces* no new elements, but that it *liberates* them from the substances exposed to its action, at the same time that it facilitates, by their liberation in the nascent state, their combination with other elements present. It is very remarkable that, under the action of a powerful electricity, substances, apparently the most insoluble, may be decomposed; this is proved by a great number of Davy's experiments upon glass, upon marble, upon the sulphates of strontian and baryta, employed as vessels filled with water.

Dynamic electricity not only liberates the elements by separating them, but it transports them,—a characteristic that appertains to this mode of decomposition alone. This has been long since established by Berzelius and Hizinger. By operating with wires of different metals, and upon solutions of various natures, either separated or mixed, sometimes different, at other times similar, at the respective poles, they succeeded in satisfactorily proving this power of transport, which accompanies the decomposing power of the voltaic pile. In order to place the different liquids in contact with the respective polar wires, they employed a syphon, the branches of which, closed by corks fitted into their extremities, and traversed by the wires, were filled to about two thirds of their height, one by a liquid, such as sulphate of potash, the other by another liquid, such as muriate of ammonia. The upper part of the syphon contained distilled water, in order to put the two liquids into communication; it was pierced at its summit by several holes, intended to allow the gases to pass out. They had concluded from all their experiments that, when electricity traverses a liquid, the principles that it contains are se-

parated; that oxygen and acids are transported to the positive pole, hydrogen, the alkalies, the earths, and bases in general, to the negative; and this, as well when the saline solutions, into which the wires that come from the respective poles are plunged, are heterogeneous, as when they are similar. The numerous results to which they had arrived, had also demonstrated to them the influence over the energy of the decomposition, of the extent of contact of the polar wires with the liquid; and the part that is played in the production of the effects observed, by the affinity of the elements of these liquids for the substance of the wires, as well as their reciprocal affinity, when several different liquids are submitted at the same time to the decomposing action.

But it is Davy, who, by the accuracy and the number of his experiments, has completely analysed this property of transport, possessed by dynamic electricity, and which must not be confounded with that, which we have already described in the preceding Chapter; for it is manifested only with decomposition. In order to study this phenomenon well, it is necessary to make use of cups or tubes of glass, in which are placed the liquids that are required to be traversed by the current; into each of these cups, when there are two (*fig.* 227.), or into the extreme cups, when there are more than two (*fig.* 228.), are plunged the platinum wires or plates, that communicate, one with the + pole the other with the − pole of

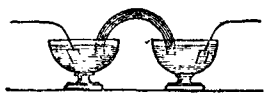

Fig. 227.

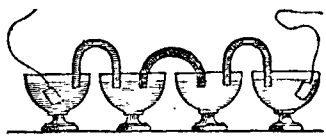

Fig. 228.

the pile; then the liquids of the cups are connected one with the other by means of hanks of cotton or asbestos, well saturated with water (*fig.* 229.), or by tubes in the form of a syphon, filled with very pure water (*fig.* 227, 228.). When we desire to collect the gases that are liberated, each of the polar wires is surrounded by a tube, closed above and open below, which is filled with the same liquid, as that contained in

the vessel into which it is plunged; and the two vessels are connected (*fig.* 230.). If, when making use of two cups,

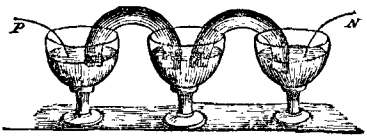

Fig. 229.

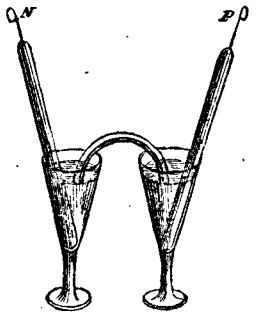

Fig. 230.

distilled water is placed in one, and a saline solution in the other, the base or the acid passes into the distilled water, according as the metal conductor, that is plunged into it, is the negative or the positive. Care must be taken always to maintain the level of the distilled water higher than that of the solution, in order that no part of the latter shall pass into the water. On taking this precaution, we may satisfy ourselves, for example, with sulphate of magnesia, that no pure magnesia passes into the distilled water, when this water is in communication with the negative pole, and that there is no trace of sulphuric acid, since a salt of baryta produces no precipitation.

In order to discover how far this property of transport extends, it is necessary to employ at least three cups (*fig.* 229.) the saline solution is placed in one of the two extreme cups, distilled water in the other, and a reagent in the intermediate cup. If this reagent is water coloured blue by tincture of litmus, on pouring a solution of sulphate of potash into the negative cup, the coloured water is not seen to be reddened by the passage of the sulphuric acid; but the first impression of redness is shown only at the extremity of the hank of amianthus, which makes communication between the coloured water and the positive vessel, namely, on the side most distant from the vessel from which the sulphuric acid comes. The

same thing takes place for alkali, when, the saline solution being placed in the positive vessel, it is transported to the negative pole. It is even easy to demonstrate that this colouration of blue water into red by acid, into green by alkali, only arises from the diffusion of the acid, which is all carried around the positive wire, and of the alkali, which is all carried around the negative wire. For this purpose, we have merely to employ, as I have done, a large tube, divided into three equal compartments, by two diaphragms of bladder, which allow the current to pass, without permitting the liquids to mix: these three compartments fulfil the office of the three cups above mentioned.

The experiment, that we have just related, shows therefore that, under the influence of the current which transports them, acid and alkali lose the property of changing the colour of vegetable blue. In order to learn to what point their chemical activity is neutralised, we must substitute for the coloured waters of the intermediate cup, liquid substances, that have more or less affinity for the acid or the base, that are transported, and be satisfied whether they are arrested in their passage by these substances. By this method, we prove that a solution of ammonia, of soda, of potash, or of lime, does not arrest, either sulphuric, nitric, or hydrochloric acids, which continue to present themselves in the distilled water of the positive cup, when salts of these acids in solution have been placed in the negative cup. If the saline solutions are placed in the positive cup, their bases are seen to present themselves in the distilled water of the negative cup, through acids, placed in the intermediate cup. It requires a tolerably long time (twenty-four to forty-eight hours), for these effects to be manifested in a very decided manner; and it is necessary, from time to time, to remove and to wash in pure water the hanks of amianthus, by which communication is established between the cups. The pile must be composed of a very considerable number of pairs, which depends also upon the kind of pile that is employed; but it is easy to determine in each case the number of pairs necessary for the manifestation of the effect, because there are always some

bubbles of gas, which, by being liberated at the polar wires, indicate the moment when the current is sufficiently powerful to pass.

There are, however, some cases, in which the substance transported is arrested by that which it traverses; sulphuric acid, for example, cannot traverse solutions of strontian and baryta; and these two bases in their turn cannot traverse sulphuric acid. Thus if we place a solution of sulphate of potash in the negative cup, distilled water in the positive, and a saturated solution of baryta between the two, we do not obtain, even at the end of thirty hours, and with a pile of 150 pairs, any appreciable portion of acid in the distilled water; but there is formed, in the intermediate vessel, much sulphate of baryta. Thus again, a solution of hydrochlorate of baryta being placed in the positive cup, sulphate of potash in the intermediate cup, potash is soon seen to appear in the distilled water, that is in the negative cup; and an abundant precipitate of sulphate of baryta is formed in the middle vessel. If the intermediate solution is sulphate of silver, hydrochlorate of baryta being placed on the negative side, sulphuric acid is seen to appear in the distilled water of the positive side, and an abundant precipitate of chloride of silver to be formed in the silver solution.

The experiments, that precede, show therefore that the neutralising power of the current has a limit, which depends upon the degree of affinity of the substance transported, for that which is contained in the solution that it traverses; that, for example, sulphuric acid is able to traverse a solution of potash, of soda, &c., without being arrested; but that it is arrested by a solution of baryta, because it forms with it an insoluble compound. They show therefore that an exchange may take place of base or acid, between the current of the solution that it is traversing, in such a manner that the current may yield to this solution the acid or the base that it was carrying, and take in its place the acid or the base of the salt dissolved.

An analogous phenomenon, and one of no less importance

for the theory of electro-chemical decompositions, is, that certain bases, that are little or not at all soluble, such as magnesia, and several metallic oxides, arising from saline solutions, placed in the positive cup, are very well able to pass into the negative cup, filled with distilled water, if the two cups communicate only by a hank of amianthus; but if there is interposed between them a vessel of pure water, still establishing, by means of hanks of amianthus, the communication between this vessel and the other two, then the particles transported fall to the bottom of the intermediate vessel, and do not go to the negative vessel.

Hitherto we have spoken only of the decomposition of salts and of water, but Davy found that water is not the only binary compound that the passage of electricity is able to separate into its elements,—that acids and oxides are also decomposable; and he thus succeeded in demonstrating that potash, soda, and the different earths are nothing more than oxides, the metal of which he succeeded in obtaining. Having taken a piece of pure potash, which had been for some moments exposed to the air, so as to become a conductor on its surface, on account of the moisture that it had attracted, he placed it upon an isolated plate of platinum, put into communication with the negative pole of a powerful voltaic pile of 250 pairs; he then touched the upper surface of the piece with a platinum point, communicating with the positive pole. There was liberated around the wire a great quantity of gas, which was recognised to be pure oxygen; and then were discovered, at the lower part of the potash, some small globules which had a brilliant metallic lustre, but which were not long in becoming tarnished, and covered with a white coating, that formed upon their surface. These globules decomposed water with great vivacity, liberating hydrogen, and oxidising with development of heat and light. In dry air they only became covered with a film of oxide which, for want of humidity to dissolve it, remained upon the surface, protecting the interior of the substance against the action of the oxygen.

A piece of soda presented exactly the same phenomena;

only it required a pile a little more powerful, in order to obtain the metallic globules; and the latter were themselves less rapidly oxidised in the air.

After having proved that potash and soda are therefore oxides of two metals, which he named *potassium* and *sodium*, Davy succeeded in obtaining a tolerably large quantity of them, by collecting them, in proportion as they were formed, in recently distilled oil of naphtha, which is without action upon them, and in which they are preserved perfectly intact. These two substances have all the properties of metals; and they have their brilliancy, presenting an aspect very similar to that of polished silver. They conduct heat and electricity; they melt, potassium at 168°, and sodium not under 180½°; they crystallise and become brittle at 32°. Their density is less than that of water.* These two metals easily amalgamate with mercury, and it is even a means of extracting them from their oxides: a globule of mercury is placed upon a piece of potash or of soda, itself placed upon a platinum plate, which communicates with the positive pole; then a platinum point is thrust into the globule, which is connected with the negative pole of the pile. The alkaline metal is then easily extracted from its amalgam by distillation conducted in oil of naphtha, and the little globules obtained either in this manner, or directly, are converted into a single button by fusion conducted also under oil of naphtha.

Davy subsequently extended his discovery to other compounds; and, thanks to his labours and to those of some other chemists, it was demonstrated that all the earths and fixed alkalies were metallic oxides, whose bases were more or less easily extracted, first by means of the decomposing force of dynamic electricity, afterwards by purely chemical processes. We shall have occasion to compare the two modes in the Chapters of the Part, which are devoted to applications, whose subject will be the employment of electricity for the extraction of metals.

The fundamental phenomena of the electro-chemical de-

* That of potassium is 0·865; and that of sodium 0·972.

compositions, that we have been describing, suffice for the present to enable us to lay down certain general principles. First, they prove to us that electro-chemical decomposition is a phenomenon of dynamic electricity, and not a phenomenon of static electricity. Indeed, everything that favours the passage of the current, facilitates decomposition. Gay-Lussac and Thénard succeeded in demonstrating this in their physico-chemical researches. They have proved that the quantity of gas liberated in the decomposition of water, very feeble when the water is pure, increases with the quantity of salt or acid dissolved in it, and consequently with its degree of conductibility; that it is also, up to a certain limit, greater in proportion as the surface of contact increases between the liquid and the polar conductors. The elevation of temperature which increases the conductibility of the liquid, facilitates its decomposition. All these results, therefore, show that it is impossible to attribute the decomposition of bodies to an attraction, exercised by the two poles over the constituent molecules; the one set positive, the other negative, and which would be analogous to ordinary electric attractions and repulsions.

Another well-established point is, that the portion of the liquid, which is decomposed, is only that which is in contact with the polar conductors, whether it be the same or different at the two poles, as the researches of Hizinger and Berzelius have proved. The intermediate liquids, when they are separated from each other and from the polar liquids, merely by porous diaphragms, or humid conductors, do not undergo any alteration in their composition, save in the exceptional cases that we have pointed out above, according to Davy. In like manner, it is upon the surface of the metals which serve as poles, that the liberated elements are deposited, as is proved by simple inspection, when gaseous and solid elements are in question, and by the employment of tests, in the case of liquid elements. As a proof that the halves of the liquid interposed between the poles are in two opposite states of electric tension, the elegant experiment is quoted; that a saline solution, sulphate of soda, for example,

coloured blue, placed in a U tube (*fig.* 231.) becomes half coloured red, and half green, when placed in the circuit of the pile, by means of two platinum wires. But this double colouration is only the effect of the diffusion of the acid and the alkali, which, liberated at each of the poles, spread gradually in the surrounding parts of the liquid. I have proved this by placing the saline solution in a vessel separated into three compartments by two bladders, which prevent the solutions contained in each of the compartments from mixing, at the same time allowing the current to traverse them. However long may have been the duration of the decomposition, the colour of the liquid contained in the middle cell has not been altered, whilst the liquids contained in the two extreme cells, into which the two poles were plunged, have entirely changed their colour.

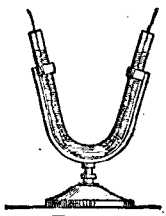

Fig. 231.

We have seen that if we have in succession several vessels, filled with acidulated water or a saline solution, and if, instead of connecting them by humid conductors, they are made to communicate with each other by metallic arcs, we then obtain, in each vessel separately, a decomposition exactly the same as would have taken place, had the liquid of this vessel been alone in the circuit. Thus, we shall obtain in the two tubes of each of the three vessels of *fig.* 232., which are filled with acidulated water, oxygen and hydrogen in the proportion that constitutes water, the oxygen being in the tubes

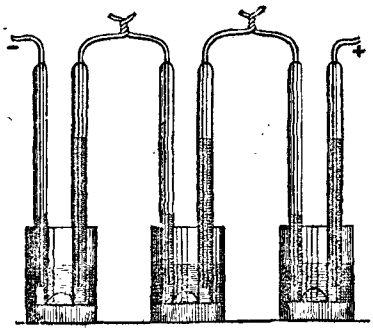

Fig. 232.

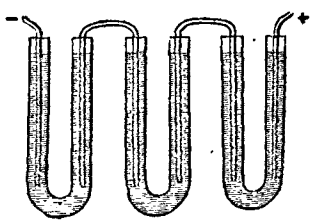

Fig. 233.

turned towards the side of the positive pole, and the hydrogen in those turned to the side of the negative pole. So also, if we have a series of U tubes (*fig.* 233.), filled with a saline solution coloured blue, and connected by platinum wires, bent in the form of an arc, and plunging by one of their ends into one of the tubes, and by the other into the following, whilst the two extreme branches communicate by platinum wires, one with the positive, the other with the negative pole of the pile, we perceive the solution become coloured red in all those branches of the tube, that are turned to the side of the positive pole, including that into which this pole is plunged, and coloured green in all those that are turned to the side of the negative pole, including that which communicates immediately with that pole. We have merely to change the place of the two poles, to perceive all the red and the green parts of the liquid repass first to blue, then those that were red pass to green, and those that were green pass to red.

An important point to notice is, that when saline solutions are decomposed, there is at the same time a gaseous liberation at the poles, which seems to indicate a simultaneous decomposition of water. However, there is an important difference to be made in this respect between the salts, whose base is manifested in a state of oxide at the negative pole, and those in which it appears in the revived metallic state; in this latter case there is, as in the former, a liberation of oxygen with the acid at the positive pole, but there is no hydrogen at the negative pole, as if this gas were employed in reducing the oxide, which forms the base of the salt. We shall see hereafter what actually takes place in this case. For the present, we shall confine ourselves to remarking that the revived metal is manifested sometimes in the state of plates adhering to the surface of the conductor that is employed for a pole, sometimes in a state of powder, sometimes in the crystalline state, or forming remarkable aborizations. One of the most elegant is that which is obtained by employing acetate of lead, and into the middle of a vessel that contains this solution, thrusting a platinum wire in communication with the negative pole of a pile, the other pole of which also com-

municates with the liquid, by means of a wire or plate that is immersed towards the edge of the vessel. If the current is not too strong, the aborizations are slowly formed, and in a very brilliant manner, whilst with a very energetic current they are confused. The force of the current, indeed, as we shall see, as well as the nature itself of the salt, submitted to the decomposing action of the electricity, has an influence over the structure of the deposits, that occur in this case.

Before extending further the study of the phenomena of decomposition, and the research of the precise laws by which they are regulated, we think it useful to make known here, the ingenious manner in which Grotthus succeeded in explaining them. Setting out from the principle laid down by Davy, and afterwards admitted by Berzelius and by Ampère, that the constituent atoms of bodies are, some electro-positive and others electro-negative, and that it is in virtue of the mutual attraction of the electro-positive and the electro-negative elements, that chemical combination is brought about, he explained in the following manner what takes place in the electro-chemical decomposition of any compound — water for example. As soon as a filament of water is placed in the circuit, it is polarised, as we have seen every conductor must be, when interposed between the poles *; but hydrogen being a body eminently positive, the molecules of hydrogen of each particle of water turn on the side of the negative pole, and the molecules of oxygen, which is eminently negative, on the side of the positive pole † (*fig.* 234.). The current passes, that is to say, there is a discharge of the consecutive molecules between each other, and of the two extreme molecules with the poles. It follows from this that the negative oxygen of the molecule of water No. 1., which is in contact with the positive pole P, is liberated against the pole of which the electricity is combined with its negative electricity, and that the positive hydrogen of the

* Vol. II. p. 63.

† In each molecule of water the particle of hydrogen is clear, and that of oxygen shaded.

molecule No. 6., in contact with the negative pole, is liberated in like manner against this pole; now the hydrogen of the

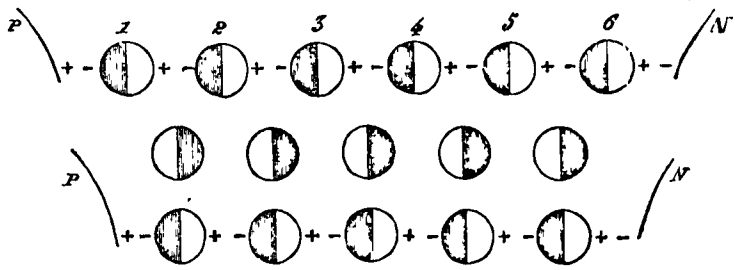

Fig. 234.

molecule of water No. 1. combines with the oxygen of the molecule No. 2., the hydrogen of No. 2. with the oxygen of No. 3., and so on to the last particle. In other words, the discharge that is brought about between the consecutive molecules of water, in order to constitute the current, drawing all the hydrogens of the pole + to the pole — and all the oxygens of the pole — to the pole +, it liberates the hydrogen of the molecule in contact with the — pole, and at the same time compels all the oxygens and hydrogens of the intermediate particles to combine together to re-form water. The second series of particles of *fig.* 234. represents these new particles of water. What the first passage brings about, the second passage brings about in like manner, namely, that the particles are polarised anew, and consequently must all make a semi-revolution in order that the oxygens may be turned on the side of the + pole, and the hydrogens on the side of the — pole, as represented by the third series of particles of *fig.* 234.; then decomposition takes place, as well as the exchange of the constituent parts, between each of these particles, with liberation of gas at the extreme particles, and so on as long as the current is transmitted. We therefore see, since there is only oxygen at the + pole, and hydrogen at the — pole, that we are no longer embarrassed to explain what becomes of the hydrogen of the particle in contact with the positive pole, and the oxygen of that which is in contact with the negative pole.

The explanation that we have been giving, taking water for the example, is equally well applicable to the decomposition of every compound body. In the case in which the solution interposed between the poles is not homogeneous, but is composed of two or three different solutions, the exchange takes place in a similar manner. Thus, if the positive pole is in contact with a solution of nitrate of potash, and the negative with a solution of sulphate of soda, the sulphuric acid of the last particle of the sulphate, and the potash of the first particle of the nitrate combine, liberating a molecule of soda at the — pole, and one of nitric acid at the + pole; then this particle of sulphuric acid combines with a second of potash, liberating a second particle of soda at the — pole, a second of nitric acid at the + pole, until finally the sulphuric acid comes also to the + pole, and the potash to the — pole; and that, conformably with the observations of Berzelius and of Hizinger, we have both acids at the + pole, and both bases at the — pole. If there is a third solution between the two, it is also by the way of decomposition and combination that the passage of the current and the transport of particles takes place. Only if the compound momentarily formed is insoluble, then, as we have seen, its elements are no longer transported to the two poles, and are replaced by those, which have not formed an insoluble compound. Thus, if the interposed solution is hydrochlorate of baryta, sulphuric acid forming with baryta an insoluble compound, the sulphate of baryta is precipitated to the bottom of the intermediate vessel, and its place at the + pole is supplied by hydrochloric acid. In like manner if the salt, placed at the positive pole, is nitrate of silver, and that placed in the middle is hydrochlorate of soda, the silver, which forms with hydrochloric acid an insoluble body, is precipitated, and soda is liberated in its place at the negative pole.

We shall see further on, that this theory very well explains the general facts as well as the secondary phenomena, which the more profound study that we shall make of electro-chemical decompositions will enable us to to discover. We merely remark in this place, that we do not admit the dis-

tinction of the elements of bodies into electro-positive and electro-negative, as it has been in general formularised,—a distinction that cannot be maintained in face of the fact, that the same body may comport itself according to the combination into which it enters, sometimes as electro-positive at other times as electro-negative; for example, chlorine, which goes to the + pole, when it is combined with hydrogen in hydrochloric acid, and to the — pole, when combined with oxygen in the chloric acids. The property in question can, therefore, be only relative; and it consists in this, that as soon as the current traverses a compound liquid conductor, it polarises the molecules of this liquid in such a way that among their elements, some become charged with negative electricity and others with positive, the same element being able, according to that with which it is combined, to become charged equally with one or with the other. We shall endeavour, when we are occupied with the electricity liberated in chemical actions, and consequently with the more intimate relations, that exist between these two kinds of force, to show that this property may easily be reconciled with the hypothesis that we have previously made; namely, that the atoms of bodies all possess a natural polarity.

Laws of Electro-chemical Decompositions. Definite Action of the Current.

It had long been thought that the presence of water was necessary, in order that a liquid body might be decomposed by the electric current. It had even been remarked as a very curious fact, that water, which, when it is pure, is very difficultly decomposed, being itself a very bad conductor of electricity, may, by dissolving them, render such bodies as sulphuric, sulphurous and other acids, conductors, which do not of themselves conduct electricity at all, or in a very trifling degree. Davy had, however, already observed, that we may employ, as liquid conductors for charging piles, such salts as chlorate of potash in a state of fusion; but he had always considered the presence of water as necessary in

the liquid, placed between the poles in order to be decomposed. It is Faraday, who, having succeeded in transmitting currents, even of a feeble intensity, through chlorides and salts, brought to the state of fusion by the action of a high temperature, has at the same time shown that these bodies were decomposed by the currents into their elements, some of which were carried to the positive pole, the others to the negative. Thus, on placing some of these solutions in fusion in small glass tubes in the form of a U, and introducing into each of the branches a platinum wire, in order to transmit the current through the substance, he found, with iodides and chlorides of lead, silver, &c., iodine and chlorine at the positive pole, and lead, silver,—in a word the metal—revived at the negative pole. But it is necessary, in order that the decomposition may take place, that the bodies liquefied by heat shall become conductors by the fact of this change of state, in order that the current may be able to pass. Now, there are a great number of bodies, such as sulphurets, perchlorides, as well as many organic substances, which do not become conductors on being liquefied, and which, consequently, are not decomposed. The reverse is equally true, namely, that every compound body, which becomes a conductor by liquefaction, is decomposed by the current; the exceptions to this rule, which Faraday cites, being only apparent, as we shall soon see. There is, therefore, a great difference between simple conductibility, which we may call physical, and the conductibility, accompanied by electro-chemical decomposition. The former, which is peculiar to elementary solid and liquid bodies, such as mercury and the melted metals*, diminishes by the effect of elevation of temperature, as we have seen as well in the case of liquids as in that of solids; the latter, which belongs to

* Inglis and Palmieri had thought that melted iodine is a conductor of electricity; but Beetz satisfied himself, by very accurate experiments, that the slight traces of conductibility, presented by iodine in a state of fusion, are due to its mixture with a small portion of hydriodic acid, which is decomposed by the current. Furthermore, bromine, liquid chlorine, melted sulphur, selenium, and phosphorus are not conductors, so that among elementary bodies, there are only the metals and carbon that conduct electricity.

compound liquid bodies, increases, on the contrary, with the heating, which favours decomposition. It follows from this that it seems almost to be a consequence of this decomposition, or that it is at least intimately connected with it, so as to form with it but one and the same phenomenon. However, Faraday and some philosophers think that compound liquids may conduct a sensible portion, however small, of electricity, without becoming decomposed; and may consequently possess a certain degree of physical conductibility. We shall examine in the sequel, when we shall have well studied the phenomena, that attend upon decomposition, and shall have determined its laws, the extent to which this opinion is well founded.

We see, therefore, that every compound body, a conductor of electricity, may be decomposed by the passage of the current, when it is in a liquid state, whether it may have been brought to this state either by solution in water or by fusion. We are now about to investigate the more precise laws, according to which this decomposition is brought about; and, in order to render our labour more easy, we shall adopt the terms introduced by Faraday into this part of the science. Thus, chemical decomposition, brought about by electricity, we shall call *electrolysis*, to distinguish it from *analysis*, which is decomposition brought about by purely chemical means, and from which it differs by very decided characteristics. Bodies susceptible of being decomposed by the electro-chemical way, we shall term *electrolytes*. Finally, we shall retain the name of *electrodes* to the conductors, that establish communication between the poles of the pile and the electrolyte.*

The first law that we encounter, and which was established by Faraday, is that the decomposing action of a current is

* Mr. Faraday calls the positive electrode the *anode*, and the negative the *cathode*; in like manner he designated as *anions* those elements of the electrolyte, that are liberated at the positive pole, and as *cathions* those that are liberated at the negative pole; giving the name of *ions* to these two classes of elements. We shall not make use of these various denominations, which do not seem to be indispensable, whilst those we have adopted are eminently useful.

constant for a given quantity of electricity. Thus, if we have several voltameters, placed one after the other so as to be traversed by the same current for the same time, it is found that the quantity of oxygen and of hydrogen gas liberated in each is similar, even though the conducting solutions and the size of the electrodes differ from one voltameter to the other. These solutions may be acid, alkaline, or saline; they may be more or less diluted; and notwithstanding they give the same quantity of gas, when they are traversed by the same current for the same time. With regard to the electrodes, it is necessary that they be of platinum, and so arranged that the gases have the shortest possible course to take in the liquid, that always dissolves more or less, which gives rise to the risk of making us suppose differences in the quantity of gas liberated. Care must also be taken, especially when the electrodes present a large surface of contact with the liquids, not to leave the gaseous mixture of oxygen and hydrogen in contact with the platinum electrodes; because platinum, by its mere contact with this mixture, brings about the combination of the two gases. It is even better to collect the gases separately, and to measure one of them, the hydrogen for example, which dissolves less easily; this is what Faraday, in general, did. We shall see in the fourth paragraph, when occupied with the influence exercised by the electrodes upon the electrolysis, the errors that may arise from the neglect of the precautions that we have been pointing out.

Thus then, when all the gas is collected, that arises from the decomposition of the acidulated or saline water, and when no secondary effect, as happens with certain solutions, disguises any portion, we obtain in the volume of this gas an exact measure of the quantity of electricity that passes; on which account it is that Faraday termed the apparatus founded upon this principle a voltameter. This is so true that, if we reduce this electricity to one-half, by placing two perfectly similar voltameters parallel to each other, the current divides itself equally between them, and liberates in each of them a quantity of gas, that is exactly

the half of what is liberated in a third voltameter, placed in the circuit in such a manner as to be traversed by the current entire. If there exists any difference of conductibility between the two parallel voltameters, because one of them has larger electrodes, or contains a more acid solution, the quantities of gas liberated in each are no longer the same, but their sum is always equal to the quantity of gas liberated in the single voltameter. M. Matteucci demonstrated this very satisfactorily.

But it is not only upon aqueous solutions, in which the water alone is decomposed, that the chemical power of an electric current is always proportional to the absolute quantity of electricity transmitted: this same property exists for all electrolytes; whence it necessarily follows that, when a like current traverses for the same time two or many compound bodies, that is to say electrolytes, it must necessarily in each of them separate their elements in a quantity proportional to their chemical equivalents.* This beautiful law was established by Faraday, by a great number of experiments. Thus he arranged one after the other, in the same circuit, a voltameter and a tube filled with protochloride of tin, placed in a glass tube into which penetrated two platinum wires, and retained in a state of fusion by a spirit lamp. One of the platinum wires that were plunged in the protochloride communicated with the negative pole of the pile, the other with one of the electrodes of the voltameter, the second electrode of which led to the positive pole. After having allowed the decomposition to go on for some time, it was interrupted; then was carefully weighed the platinum wire covered with tin, whose weight had previously been

* We understand by chemical equivalents the relative weights of the elements, that enter into the composition of a body. Thus the equivalent of hydrogen is 12·50, that of oxygen being 100, whence it follows that the equivalent of water is 112·50, which signifies that 100 grains of oxygen combine with 12·50 of hydrogen to make 112·50 of water. The equivalent of tin is 735·29, and that of chlorine 442·65; whence it follows that 735·29 of tin combine with 442·65 of chlorine to form 1177·94 of chloride of tin. In like manner, 100 of oxygen combine with 735·29 of tin, in order to make 835·29 of oxide of tin; and 442·65 of chlorine make, with 12·50 of hydrogen, 455·15 of hydrochloric acid.

determined; this weight gave 3¼ grs. as the weight of the tin, arising from decomposition; the weight of the water decomposed, estimated from the gaseous volume measured with care in the voltameter, was found to be about 0·49 grs; which gives 735 for the equivalent of the tin, that of water being 112, a number that is indeed the truth. The protochloride of tin, that remains after the operation, is perfectly pure, in such a way that it is evident there has been liberated at the positive pole a quantity of chloride equivalent to that of the metallic tin carried to the negative electrode. Only the secondary actions, such as that of chlorine upon the reduced metal, when the two electrodes are very near to each other, sometimes render the weight of the reduced metal too feeble. With the iodides, which are equally decomposed in the state of fusion, the same inconvenience is presented, on account of the formation of periodides at the positive electrode. In general, many precautions are necessary, and a particular choice of electrolytes, in order that the laws may be manifested in a very distinct manner, without being disturbed by secondary effects.

In order to make it come out well, Faraday endeavoured to place several different electrolytes one after the other on the route of the current, for example, acidulated water in the voltameter, protochloride of tin, and chloride of lead; and he obtained quantities of tin, lead, chlorine, oxygen, and hydrogen equivalent to each other. It is evident, in this case, that it is the worst conducting of the electrolytes, that determines the total effect,—an effect which is the same in all.

Thus we may regard as completely established that the chemical action of electricity is *definite*, and that *the same quantity of electricity, or the same electric current, decomposes chemically equivalent quantities of all the bodies, that it traverses:* whence it follows that *the weights of the elements, which it separates in these electrolytes, are all, in respect to each other, as the chemical equivalents of these elements.*

The law that we have just established must be general; but when we endeavour to prove it for the case of compound bodies, others than binary, and for that in which these

compounds are themselves dissolved in an electrolyte, such as water, we encounter very great difficulties, one of the chief of which is the formation of secondary products, which we have frequently some difficulty in distinguishing from the direct products of decomposition. Thus, when we wish to decompose a solution of ammonia, in which the precaution has been taken of dissolving sulphate of ammonia, in order to render it a better conductor, we obtain very pure nitrogen at the positive electrode, and hydrogen at the negative, in the proportion of 3 or 4 volumes of hydrogen to 1 of nitrogen. It seems to follow from this that the ammonia alone has been decomposed; and yet, if we place a voltameter in the same circuit, we find that hydrogen is liberated in it in exactly the same quantity as in the ammoniacal solution; which seems to prove that, in the latter, the water alone has been decomposed, and that the nitrogen, which is manifested at the positive electrode, is merely the secondary result of the action upon the ammonia of the nascent oxygen, arising from the decomposition of the water; much more as this nitrogen is frequently mixed with a little oxygen, and as its proportion varies with the greater or less degree of concentration of the solution.* Thus again if we decompose nitric acid, which is a very good conductor, we obtain oxygen at the positive electrode, and there is no gas at the negative; but we find there nitrous acid and deutoxide of nitrogen, which, by dissolving, render the acid yellow or red: is this effect the result of the direct decomposition of the nitric acid into oxygen and nitrous acid, or deutoxide of nitrogen? or rather the decomposition of the water contained in the acid, the oxygen of which appears at the positive electrode, whilst the hydrogen deoxidizes in part the acid, at the negative electrode? What would seem favourable to the second hypothesis is that, if nitric acid is

* We should be rather disposed to admit that it is the hydrated sulphate of ammonia that is decomposed, since while the hydrogen of the ammonia and that of the water are liberated at the negative electrode, sulphuric acid, the nitrogen of the ammonia, and the oxygen of the water go the positive electrode, and that there perhaps the nascent oxygen decomposes a part of the free ammonia of the solution.

dissolved in an equal volume of water or more, we obtain on the negative electrode a gaseous liberation, the quantity of which varies according to the differences in the strength of the acid, or in the force of the current; and, on placing a voltameter in the same circuit, we find that oxygen is liberated equally in both solutions, which seems to prove that in the acid, as in the voltameter, water alone is decomposed. However, these conclusions of Faraday's, as we shall see, are not altogether accurate. According to the same author, sulphuric acid is not directly electrolysable; but in certain cases, sulphur is deposited at the negative electrode, by the reaction of the hydrogen, arising from the decomposition of the water. Hydrochloric acid, on the other hand, suffers a direct and definite decomposition, as do also hydriodic, hydrobromic, and hydrocyanic acids; this follows from the comparison of the hydrogen, liberated by the electrolysis, with the hydrogen liberated in a voltameter, placed in the same circuit.

But what is especially important to study is that which takes place in the decomposition of a saline solution. We have seen that with salts, having alkaline or earthy bases, we obtain oxygen and acid at the same time, at the positive pole, hydrogen and alkali at the negative, whence it seems to follow, that the water and the salt are both decomposed at the same time. Mr. Daniell, who made numerous experiments on this subject, first satisfied himself that the decomposition of one equivalent of water is accompanied by that of an exact equivalent of the saline solution. In order to arrive at this result, he had divided a voltameter, by means of a porous partition, into two equal compartments, one of which contained the positive and the other the negative electrode, and both of which were filled with a solution of sulphate of soda, which covered the electrodes. The gases hydrogen and oxygen, arising from electrolysation, were separately collected and measured with care; then, after having allowed the experiment to continue for a sufficiently long time, he determined exactly the quantity of free acid, that was found in the positive compartment, and that of alkali which was in

the negative; and he thus found that there was an equivalent of each at the same time that there was an equivalent of water decomposed. He had previously assured himself that the porous partition, although it allowed the current to pass, did not suffer the liquids to mix. The same experiment was repeated, by placing in the circuit an ordinary voltameter, charged with a solution of sulphuric acid, the electrodes of which were of the same dimensions as those of the voltameter of two divisions, filled with sulphate of soda. Now, the quantities of gas liberated in the two voltameters were sensibly equal; and there was found besides in that, in which the sulphate of soda was placed, the same quantity of free acid and alkali. Thus, if we admit that the current decomposes, at the same time, the water and the sulphate of soda, we arrive at the extraordinary conclusion that the same current, which separates only one equivalent of oxygen from one of hydrogen, in one of the voltameters, is able to separate in the same time in the other, one equivalent of oxygen from one equivalent of hydrogen, and one equivalent of sulphuric acid from one equivalent of soda. What is curious is, that the temperature of the liquid rises considerably in the vessel in which the sulphate of soda is placed, and very little in that in which is the acid solution. The results were the same, on substituting nitrate of potash for sulphate of soda. By substituting in the preceding experiments, sulphuric acid diluted with water for sulphate of soda in the cell with double compartments, Daniell established a very decided transport of acid to the positive electrode; and he found that there passed about the fourth of an equivalent of acid for an entire equivalent of water decomposed. Faraday had previously obtained a result very nearly similar, except a little more powerful.

It remained therefore to discover how the current acted in the double decomposition of an equivalent of water and of salt. For this purpose, Daniell devised to place in the same circuit, in which the voltameter with the double cell, charged with a saturated solution of sulphate of soda, was situated, some chloride of lead, retained in fusion in a tube by means

of a spirit lamp; a platinum wire served as a negative electrode to the chloride and a small rod of plumbago as positive electrode. Now, the platinum wire, which weighed before the experiment 5·44 grs. attained to a weight of 27·1 grs., which makes for the lead alone, that formed a very distinct button, adhering to the wire, a weight of 21·66 grs. In the voltameter there had occurred decomposition at once of a quantity of water and of a quantity of sulphate of soda, equivalent, each separately, to the weight of chloride of lead decomposed. This experiment therefore shows to us clearly that we cannot admit that there has been at the same time direct electrolysation of an equivalent of water and of an equivalent of salt by the same force, that electrolyses an equivalent of chloride of lead. To the support of this conclusion, we will note also the following fact, that, if we take a plate of tin for positive electrode in the voltameter with double cells, and charge this voltameter with a solution of chloride of sodium and place it in the circuit, still with the chloride of lead, we find that the loss in weight of the tin, which is attacked by the chloride, and the volume of hydrogen liberated at the negative platinum electrode, to which the soda is also carried, represent the decomposition of a quantity of chloride of sodium exactly equivalent to the quantity of chloride of lead decomposed. The only manner for accounting for this result is to admit that the dissolved chloride of sodium is alone decomposed, that the chloride is absorbed by the tin, and that the sodium being carried to the negative electrode reacts upon the water, oxidises, liberating its equivalent of hydrogen, which is nothing more than a secondary product, due to an effect purely chemical, and not to the direct electrolysation of the water.

We are thus led to regard as a fundamental principle that the electric force, which we measure by its definite action, in any point of the circuit, cannot decompose more than an equivalent proportion in another point of the same circuit; so that the current which we have measured, by its electrolysation upon the chloride of lead, cannot be at the same time sufficient to electrolyse one equivalent of chloride of sodium,

and one equivalent of water in the same voltameter between the same electrodes. It follows, from this manner of regarding it, that, in the decomposition of the dissolved sulphate of soda, we must admit that the sulphate in like manner is alone decomposed and not the water; that the oxygen of the oxide of sodium goes with the sulphuric acid to the positive electrode, where it is liberated, whilst the sodium is carried to the negative electrode, where it decomposes the water, and becomes soda, liberating its equivalent of hydrogen, which in like manner is nothing more than a secondary product. With salts, whose metallic base, such as lead or copper, is incapable of decomposing water at ordinary temperatures, the pure metal is found deposited at the negative electrode. This deposit is a direct effect of decomposition, and it is not due, as has long been assumed, to the reduction of the oxide, by the hydrogen arising from the electrolysation of the water, which would have occurred at the same time as that of the salt. Direct experiments made, by substituting, for solution of sulphate of soda, that of sulphate of copper in the circuit, in which there is melted chloride of lead, confirm this explanation, which is completely in accordance with the ideas of Davy and Dulong on the composition of salts, which they regard as binary compounds, analogous to the chlorides. Thus, like as chloride of sodium is a compound of one equivalent of chlorine and one equivalent of sodium, a sulphate of soda is a compound of one equivalent of *oxysulphion*, and one equivalent of sodium, — an equivalent of oxysulphion being formed of one equivalent of oxygen and one equivalent of sulphuric acid. We see, therefore, that according to Daniell's experiments, Faraday's ideas on secondary actions, due to the direct decomposition of water in solutions, must be modified, as we have anticipated.

We have now established, with Faraday, the law of the definite action of the current, and with Daniell, that of the immediate decomposition of salts, dissolved in water. Now, before seeing whether Faraday's law extends to all classes of compounds, and whether, in particular, it is applicable to those in the decomposition of which there enters more than

one equivalent of one of the constituent elements, we shall turn our attention to considering how decomposition is brought about, when two or more electrolytes are mixed.

M. Matteucci was the first, after Faraday, who by numerous labours followed out this class of researches. After having demonstrated that the law of this definite action of the current governs, as well the chemical action that takes place in the interior of the pile between the pairs, as that which takes place between the poles,— an important point for the theory of the pile,—he had proved that the electrolysis of combinations of oxides with acids gives the same equivalent of metal, as that of the oxides themselves, as well when these combinations are dissolved in water, as when they are liquefied by heat: this agrees with the results obtained at a later period by Daniell.

Indeed, setting out from the law discovered by Faraday, that oxides, chlorides, iodides, and binary combinations in general, are decomposed into their equivalents, M. Matteucci had wished to determine what would take place, when these combinations were of the second order, namely salts. Consequently, he had submitted successively to the action of the current acetate of lead, both melted and dissolved, taking care to place at the same time in the circuit a voltameter with acidulated water. For ·366 cubic inches of mixed gases, which correspond to ·049 grains of water decomposed, he obtained ·58 grains of lead at the negative electrode, as well in melted as in dissolved acetate, which corresponds to 1287, the equivalent of lead, a number very near to that, which is adopted by chemists. He had made the same experiment upon nitrate of silver, and he had found for ·366 cubic inches of gaseous mixture in the voltameter, ·60 grains of silver, which corresponds to 1356 for the equivalent of silver; melted and dissolved nitrate gave the same results. Neutral borate of lead melted gave for ·366 cubic inches of the mixture, ·58 grains of lead at the negative electrode, as the acetate had done.

The reduced metal is not, therefore, the effect of a secondary action, arising from the decomposition of water; it is evident

that salts are decomposed directly, as well when they are brought to the liquid state by their solution in water, as when they are brought to it by the effect of heat. The difference, therefore, that exists between an oxide and a salt, is that, whilst for both equally there is an equivalent of metal transported to the negative electrode, there is for the salt an equivalent of acid transported to the positive electrode with an equivalent of oxygen. M. Matteucci perfectly satisfied himself of this, by taking as electrolytes, neutral benzoates, of potash, lime, zinc, lead, and silver, which are all more or less soluble in water, whilst benzoic acid itself is insoluble. This acid might therefore be easily collected at the positive electrode upon filtering-papers, then properly washed and dried. It was weighed, and for its weight was obtained a number very nearly equal to its equivalent, which could easily be proved by collecting and measuring the other products of the decomposition, namely, the oxygen and the base of the salt; only a small quantity of benzoic acid disappeared by the fact of the water dissolving a little of it; so the number obtained was slightly lower than the equivalent.

M. Matteucci has, in like manner, extended Faraday's law to the case of the mixture of two electrolytes, by showing that they are both decomposed; the sum of the quantities of each of them, that are decomposed, is equivalent to the quantity that is obtained, by decomposing a single one, by a current of the same force and of the same duration, which proves that in this case also, the chemical action of the current is definite. With regard to the proportion of each of the electrolytes that is decomposed, it depends upon their nature, and upon the proportion itself in which they enter into the mixture. Thus, with solutions a little diluted of hydro-chloric and hydriodic acids, of chlorides and of iodides, these compounds alone were decomposed, whilst the water was also, when its proportion in the solution, together with the force of the currents, was increased.

M. Becquerel, senior, who had also turned his attention to the decomposition of mixtures, had thought he had discovered in it a means of measuring affinities. Having mixed to-

gether nitrate of silver, and nitrate of copper, in a proportion such that there were the same number of equivalents of each, he had observed that the nitrate of silver alone was decomposed; in like manner, in a similar mixture of nitrate of lead and nitrate of copper, the nitrate of copper alone was decomposed. But if in the mixture the proportion of that one of the two nitrates which had not been decomposed, was increased, there arrived a moment when it also was decomposed. Thus, on operating upon a solution which contains one equivalent of nitrate of silver, equal to 1·54 grs., it was necessary to add 67 equivalents of nitrate of copper, in order that there might be at the negative electrode a metallic precipitate, composed of one equivalent of each of the two metals. M. Becquerel hence deduced the conclusion, that the current is then divided into two perfectly equal parts, between the two nitrates, because there is produced on each of them the same chemical effect; and that it overcomes in them equal resistances, which are the affinities existing between the constituent parts of the two salts. It is by increasing the mass, that is to say the number of the particles, exposed to the action of the current, of that one of the nitrates which is the least decomposable, that we arrive at this equality of electrolytic effects; whence M. Becquerel concluded, that we ought to find in the relation of the masses necessary, in order to there being an equivalent of each decomposed, the measure of the forces, that unite the oxygen and the nitric acid to an equivalent of silver and of copper. We cannot conform to this conclusion; because, without denying that affinity may play a part in the result obtained, it is incontestible that the relative conductibility of the two mixed nitrates acts a much larger part in it; and that these two properties seem to be independent of each other.

The influence of conductibility in the phenomena observed by M. Becquerel, is found to be confirmed by the researches that M. Matteucci has also made, but following a different method, in order to discover the relation that may exist between the electrolysation of certain combinations, and the chemical affinity of the elements of which they are formed.

We have already seen * that he had succeeded in showing that all the compounds which, melted and anhydrous, conduct the current better than water, are always better conductors than their aqueous solutions, even the most concentrated; and that, in order that two aqueous solutions of two compounds shall have the same conductibility, it is necessary that the one, whose compound is the worst conductor in the state of fusion, should be the most concentrated. Now on operating in the same manner, he found that that which is true for conductibility, is true also for electrolysation. Thus, if two voltameters are placed parallel in the same circuit as an ordinary voltameter with acidulated water, it is found, for example, that one equivalent of nitrate of silver on the one part, and four equivalents of nitrate of lead on the other part, added to 100 grs. of water, give two solutions equally electrolysable; we have for ·732 cub. in. of gaseous mixture in the principal voltameter ·617 grs. of lead, and ·585 grs. of silver in each of the other two. In like manner, it requires $2\frac{1}{2}$ equivalents of nitrate of copper, and 1 of nitrate of silver, in order to obtain two liquids equally electrolysable. In all cases, it follows, as a matter of course, that the sum of the equivalents of the two metals is equal to the equivalent of hydrogen liberated in the principal voltameter, which is always placed in the circuit. We see that the proportions found by M. Matteucci are very different from those of M. Becquerel, which proves that the mutual action of the two mixed salts exercises an influence over the result. The solvent has also an influence, although the body dissolved is alone decomposed: two solutions of nitrate of silver of the same density, one in alcohol and the other in water, the former containing consequently much more nitrate than the latter, being each placed in one of the partial voltameters, give, the former, ·877 grs. of silver, the latter, .862 grs., numbers almost equal, and the sum of which corresponds to 1·09 cub. in. of the gaseous mixtures, arising from the decomposition of water, in the principal voltameter.

* Vol. II. p. 119. and following.

The two solutions are therefore equally electrolysable; and yet they contain in the same volume very different quantities of nitrate of silver, which is the cause of their having the same density.

In order to compare the electrolysation of different compounds, M. Matteucci always proceeds in the same manner, namely, by placing in the circuit a principal voltameter, filled with water, acidulated with sulphuric acid to the maximum of conductibility (1·232 of density); then, in succession, parallel to each other, so that the current may divide equally between them, a second voltameter similar to the former, and the dissolved or melted substance, that is the subject of the experiment. When this substance is protoxide or iodide of lead, chloride or nitrate of silver, it transmits all the current, and none passes through the secondary voltameter; with chloride or acetate of lead, there is a decomposition in the secondary voltameter, more powerful with the acetate than with the chloride, which would indicate that it is less electrolysable. By substituting melted acetate of lead for the secondary voltameter, he found with oxide of lead, placed parallel, for ·732 cubic in. of gaseous mixture in the principle voltameter, ·138 to ·154 grs. in the acetate, and ·924 grs. in the oxide; with nitrate of silver, ·061 grs. of lead in the acetate, and 1·07 grs. in the nitrate. Thus free oxide of lead is more electrolysable than the same oxide combined with the acid; and nitrate of silver is still more so. By comparing successively the chlorides of lead and silver with the acetate, he found ·154 grs. of lead in the acetate, and consequently about ·924 grs. in the chloride; whilst with chloride of silver, the acetate is not decomposed. Iodide of lead gives very nearly the same result as the chloride and the oxide, which proves that certain compounds are equally electrolysable. On the other hand, if we place parallel with acetate of lead protochloride of tin, we always obtain for ·732 cubic in. of the gaseous mixture in the principle voltameter, ·985 grs. of lead in the acetate, and scarcely ·046 grs. of tin in the protochloride.

M. Matteucci concluded from all these facts, that compounds more easily allow themselves to be decomposed,

as the chemical affinity by which their elements are united is less powerful, which is the converse of Faraday's opinion, who considers, on the contrary, that the most electrolysable compounds are those whose elements have the greatest affinity. With regard to ourselves, we are able to see, in these various phenomena, nothing more than the result of the greater or less resistance, which the various liquids present to the transmission of the current and consequently to their electrolysation; properties, the relationship of which is ignored, if indeed it has any existence; it is even a point, upon which conjecture differs altogether, since we see that Faraday and Matteucci have in this respect diametrically opposite opinions. However, it would seem that combinations, such as pure water, whose elements have the greatest affinity for each other, would indeed be those that have the least conducting power, and which are consequently the least electrolysable.

Another question, that here presents itself, is to ascertain whether the compounds formed by the combination of one equivalent with two or several equivalents are decomposable, like those which result from the combination of one equivalent with a single equivalent; and in the case in which they might be decomposable, what is the law by which their electrolysation is governed. Two philosophers, MM. Matteucci and Becquerel, have equally studied this important point.

Mr. Faraday had thought that compound salts, decomposable by the current, were those that are formed of the combination of one equivalent of one element with a single equivalent of another; not that they are all necessarily so, since there are several, such as the chloride of sulphur, the protochloride of phosphorus, that of carbon, which are not so, not being conductors; but Faraday allowed that they alone would have been susceptible of being electrolysed, whilst the compounds, formed of one equivalent with two or several equivalents, would be neither conductors nor electrolysable; two alone would be conductors exceptionably, periodide and perchloride of mercury; but, although con-

ducting the current, they would not be decomposed by it. M. Matteucci, in examining this point more closely, has succeeded notwithstanding in decomposing combinations, into which there enter more than two equivalents. The bodies, to which his experiments have been directed, were protochloride of antimony and the two chlorides of copper. The first could be placed in a state of fusion in the circuit with a voltameter; and experiment gave a liberation of chlorine at the positive electrode, and ·123 grs. of antimony at the negative, for a gaseous liberation of ·366 cub. in. in the voltameter, which corresponds to ·079 grs. of water decomposed.* Now these ·123 grs. of antimony represent only a third the number, that is the equivalent of that metal, for one equivalent of water decomposed. With regard to the two chlorides of copper, as they attacked the electrodes of gold and platinum, it was necessary to dissolve them in water; very concentrated solutions of them were made, and he was able to establish, by comparing their electrolysis with that of the water of the voltameter, that they were truly decomposed directly, the more so as there was only chlorine, and no oxygen, at the positive electrode. At the negative electrode was obtained one equivalent of copper, with the protochloride, but only half an equivalent with the bichloride.

M. E. Becquerel, by operating upon the dissolved chlorides, both that of antimony, as well as that of copper, has obtained for the latter the same result as did M. Matteucci; but for the former, he has found there was deposited on the negative electrode $\frac{2}{3}$ of the equivalent of antimony. He attributed the great difference, that exists between his result and that of Matteucci, to the fact, that, in the experiments of this latter philosopher, the chlorine attacks and redissolves a part of the antimony. In order to be secure from this inconvenience, M. E. Becquerel arranged his apparatus so as to place the two electrodes in two different vessels filled with the same solution, causing the

* In a subsequent experiment, M. Matteucci found, for ·576 cub. in. of gaseous mixture in the voltameter, ·208 grs. of antimony. He also sometimes arrived at a higher number; and he discovered that fresh experiments are necessary, in order satisfactorily to establish the law of the decomposition of this body, so difficult of electrolisation by direct means.

two liquids to communicate by means of a little syphon, which is charged when the vessels are filled. In the annexed figure (235.), the two glasses are placed upon the plate of an air pump, and covered with a receiver, furnished with a stop-cock and pierced with two openings, which allow

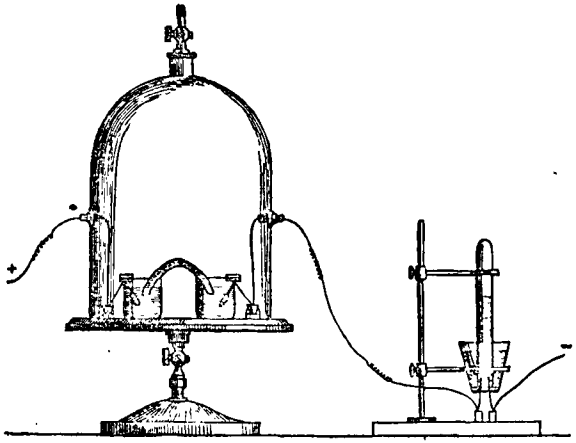

Fig. 235.

of the introduction by each of a wire into the receiver, so as to place the decomposing plates in the circuit by means of two small cups filled with mercury. The negative electrode is of platinum, and the positive may be of different metals. The apparatus communicates with a voltameter placed outside the receiver; for the latter is used for making a vacuum in order to protect the electrolytic liquids, which are alterable in the air, and to place them within another gaseous medium. In the case in which melted and not dissolved chlorides are operated upon, this apparatus cannot be employed; for it is necessary to retain the two electrodes in the middle of the mass, and to operate rapidly. The following are two experiments, made in this manner by M. E. Becquerel: —

Gas liberated in a Voltameter at 0 & 30 in.	Weight of Water decomposed.	Antimony at the Negative Electrode.
2·989 cub. in.	·331 grs.	1·63 grs.
5·561 „	·755 „	3·58 „

Now, the equivalent of antimony is 806·45, that of water being 112·5; in order that an equivalent of antimony should be deposited, it would be necessary that there should be at the negative pole in the first experiment $\cdot331 \times \frac{806\cdot45}{112\cdot5} =$ 2·372 grs.; and in the second $\cdot755 \times \frac{806\cdot45}{112\cdot5} = 5\cdot412$ grs. If we take $\frac{2}{3}$ of these two numbers, we find 1·581 grs., and 3·608 grs.; the numbers nearly given by the experiment.

The experiments that precede, as well as those made upon several other chlorides, both simple and compound, such as the bichloride of tin and the perchloride of iron, have led M. E. Becquerel to admit that, for an equivalent of water decomposed, or, which comes to the same thing, for one equivalent of electricity employed, it is always one equivalent of chlorine that is disengaged at the positive electrode, and consequently a corresponding quantity of base at the negative electrode. This is the reason why, with the chlorides of silver, tin, iron, there is one equivalent of metal for one equivalent of chlorine; the same with the bichloride of copper, all the chlorides containing one equivalent of chlorine, and one equivalent of metal; but with the protochloride of copper, which contains two equivalents of copper for one of chlorine, there are two equivalents at the negative electrode for one of chlorine at the positive; with perchloride of iron, and perchloride of antimony, each of which contains two equivalents of metal for three of chlorine, or, which comes to the same thing, $\frac{2}{3}$ of an equivalent of metal for one of chlorine, we obtain at the negative electrode only $\frac{2}{3}$ of the equivalent of metal, for one equivalent of chlorine at the positive.

M. E. Becquerel thought he might be able to extend the law that he had found for the chlorides, to the iodides and the bromides, as well as to oxides and to salts, so that there is always one equivalent of the acid element (composed, in the case of salts, of one equivalent of oxygen, and one equivalent of acid), which goes to the positive electrode, and one corresponding quantity of base to the negative. It was by operating upon the salts of lead, such as the nitrates, the nitrites, and

the hyponitrites, that he proved the existence of the law for salts; he has also verified it with two salts of copper, submitted to the action of the same current, and one of which, the hyposulphite of the protoxide of copper, gave ·8162 grains of copper at the negative electrode, whilst the nitrate of bioxide of copper, placed in the same circuit, gave only ·4004 grains, that is to say, one-half less: he obtained the same result with the protoxide and bioxide of copper, dissolved in ammonia.

We ought to bear in mind, that, notwithstanding the labours of MM. Matteucci and E. Becquerel, there is much to be done in order to discover the exact mode of the action of electricity upon compounds, into the formation of which more than two equivalents enter; unfortunately, the number of these compounds, which are conductors and susceptible of being electrolysed, is very inconsiderable. There are even some among those that M. E. Becquerel employed, which, like the bichloride of tin, do not conduct the current, even when they are melted; and although in the state of solution they become conductors, this can only be on account of their having undergone some alteration, in combining with water. We are not therefore very certain that these chlorides are decomposed directly, and that there do not happen some of those secondary actions, which are so difficult of detection, and which disturb the simplicity of the results. M. E. Becquerel himself points out some examples, in the decomposition of numerous acetates of lead, which is almost always the result of a secondary effect.

We shall terminate this paragraph by returning to a point upon which all the philosophers, who have directed their attention to electrolysis, as well MM. Matteucci and E. Becquerel, as Mr. Daniell, are agreed, namely, the manner of regarding the decomposition of salts and of acidulated water. With regard to that of salts we have already shown, that it is the metal and not the oxide, except in certain exceptional cases, which we shall examine in the following paragraph, that is transported to the negative electrode. It is thus explained, why, when salts are decomposed, whose

oxides are not soluble, such as those of magnesia and zinc, by placing their solutions at the positive electrode, and making them communicate by a moist conductor with distilled water, into which the negative electrode is plunged, it is found that the magnesia and the oxide of zinc are arrested at their entrance into the distilled water, where they remain in suspension, instead of going on to the negative electrode. It is clear that magnesium and zinc, which in their saline solutions were transported from the + pole to the − pole, exchanging, according to the theory of Grotthus, from molecule to molecule, their oxygen and their acid, so as always to form a soluble salt, on arriving at the water, find nothing more than oxygen without acid; it is therefore no longer a salt but an oxide that is formed; and as this oxide is not soluble, it goes on no further; it is then the hydrogen of the first molecule of water, that has met the magnesium or the zinc, which travels in their place by way of exchange from molecule to molecule as far as the negative electrode. Suppose, for example (*fig.* 236.), six consecutive molecules

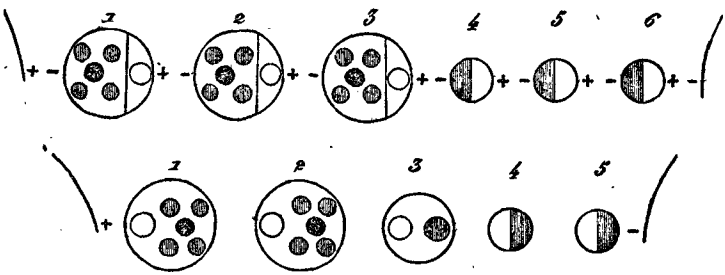

Fig. 236.

of which Nos. 1, 2, and 3. (sulphate of magnesia) are composed of 4 equivalents of *oxygen*, 1 equivalent of *sulphur*, and 1 equivalent of *magnesium* *, and the Nos. 4, 5, and 6. (water) are composed of the oxygen equivalent, and the hydrogen equivalent: the current passes, polarises them, and decomposes them. The 4 equivalents of oxygen and the equivalent of sulphur of the molecule No. 1., are liberated under the

* The white circle and the semicircles represent magnesium and hydrogen; the grey, oxygen; and the black, sulphur.

form of sulphuric acid and oxygen at the positive electrode, and the equivalent of hydrogen of the molecule No. 6. at the negative electrode. The magnesium of No. 1. combines with the *oxy-sulphion* of No. 2., the magnesium of No. 2. with the oxy-sulphion of No. 3., the magnesium of No. 3. with the oxygen of No. 4., the hydrogen of No. 4. with the oxygen of No. 5., and the hydrogen of No. 5. with the oxygen of No. 6. There are then, therefore, no more than five molecules, the third of which, oxide of magnesium, remains suspended in the liquid. The lower series of molecules of *fig.* 236. represents these molecules at the moment of the exchange of their constituent parts, and before they have been polarised anew by the current, as they are in the upper series. If the oxide is soluble, like that of sodium or potassium, the phenomenon takes place in the same manner, only the potassium and the sodium dissolve, in proportion as they arrive in the water; but it is very easy to prove that it is at the points of contact between the saline solution and the water, and not at the electrode, that they are first deposited.

M. E. Becquerel has explained in a very ingenious manner, by the same theory, the mode in which the decomposition of oxygenated water is brought about: a very interesting experiment, that he has made by placing oxygenated water in a small glass, and taking as a positive electrode a platinum wire, which passes into a glass tube closed by a spirit lamp, so that the very fine end of the wire is alone employed to decompose the liquid; there is then placed over the wire a small graduated receiver, and the oxygen alone is collected. An ordinary water voltameter is at the same time placed in the circuit. The following is the comparative result of two experiments:—

	Oxygenated Water. Gas liberated.	Ordinary Water. Gas liberated.
1st Exp.	18·5 oxygen.	9·3 oxygen.
		18·6 hydrogen.
2nd Exp.	26 oxygen.	13·2 oxygen.
		24·3 hydrogen.

We perceive that, in the oxygenated water, there is liberated double as much oxygen, at the positive electrode, as in

ordinary water. At first sight this result seems in opposition to the law established by M. E. Becquerel for the electrolysis of multiple compounds, in virtue of which there is always one equivalent of oxygen, chlorine, or acid for one equivalent of electricity or of water decomposed; now, we find two in the oxygenated water, instead of one. But, if we regard the oxygenated water, as we have done, for saline solutions, as the combination of one equivalent of water with one equivalent of oxygen, the equivalent of oxygen accompanying the place of acid, the base, which is the hydrogen, goes to the negative electrode, whilst the two equivalents of oxygen, one of which occupies the place of the oxide, go to the positive electrode. The same thing takes place here as with acidulated water, which may be regarded as an hydrate of sulphuric acid; for example, the hydrogen of this hydrate being deposited at the negative electrode, whilst its oxygen and acid are liberated at the positive. This is demonstrated by the numerous experiments made upon this subject, by various philosophers, and especially by Daniell and by Miller.*

Apparent Exceptions to the Laws of Electrolysis, and Confirmation of these Laws.

We have been establishing the law of the definite chemical action of the current, which consists in this, that a same quantity, namely, one equivalent of electricity, always decomposes one equivalent of an electrolyte. We have seen that this law, which is general, when the combination submitted to electrolysis is composed of only two equivalents, must necessarily be modified in the cases, in which there enter into the compound more than one equivalent of one of its elements. We have noticed that, notwithstanding the labours of MM. Matteucci and E. Becquerel, a fresh examination is still necessary, in order to recognise all the modifications which the law must undergo in this case, and which are

* For further details see the final note *E*.

probably different in the various compounds with multiple proportions.

If we set out with the idea laid down in the outset by Faraday that the current, which acts in electrolyses, is only *the chemical force put into circulation and transported integrally from one point to another, under the form of current and acting at a distance instead of acting only at contact,* the law of electrochemical equivalents is a necessary and rigorous consequence of this; for the same chemical force must decompose everywhere an equivalent of the compound body. However, this law is frequently disguised by a crowd of circumstances, in the midst of which it becomes so difficult a matter to discern it, that its generality has been placed in doubt. Thus it has been thought that, among compound bodies, there were some which might conduct the current, after the fashion of metals, without being decomposed; we have been led to admit that, in a great number of cases of electrolysis, the two poles possessed an unequal power of decomposing and of transport; in a word, many anomalies and exceptions to the electrolytic law have been pointed out. But, in studying them, we are about to show that they are only apparent, and that they may all be explained, by taking account of the secondary actions, that arise from the liberation of the elements which, in a nascent state, have a chemical activity altogether peculiar, and form modifications that are constantly accruing, to the very nature of this electrolyte, which, consequently, cannot remain identical, by the operation of new substances, arising either directly or indirectly from the electrolysis. It is especially to the variations of conductibility which occur in the different parts of the electrolytes of this appearance, that the principal apparent anomalies are due.

Faraday was himself the first to indicate, as forming an exception to the electrolytic law, that he had discovered certain compounds, such as sulphuret of silver, and bi-iodide of mercury, as capable of conducting the current, when their temperature was raised, without being decomposed. These exceptions, and others also of the same kind, have disappeared, thanks to the researches of M. Hittorff, and of M. Beetz.

The former has found that sulphuret of silver is decomposed, even at the ordinary temperature*: there forms, at the negative electrode, a brilliant spot of metallic silver, which always remains very small, because the sulphur, deposited upon the positive electrode, is not long in arresting the current, at least when this electrode is neither silver nor another metal, capable of combining with sulphur. If the operations are carried on at a high temperature, the sulphuret becomes as good a conductor as a metal; and yet, even after an experiment of long duration, there is but a small quantity of sulphuret decomposed; and the reduced silver is far from being equivalent to the hydrogen released in a voltameter placed in the same circuit. This is due to the circumstance that the silver, reduced to the metallic state by electrolysis, finishes by establishing between the two electrodes a communication, by which the current passes entire. It is true that the increase of conductibility disappears, when the sulphuret returns to the ordinary temperature; but this effect is due to the rupture of metallic communication by the cooling of the mass; it is indeed impossible to admit that the sulphuret can, at an elevated temperature, transmit the current without being decomposed; for, if we take as a positive electrode, a plate of zinc, or of any other metal that is not able to combine with sulphur, some sulphur is always deposited upon this electrode, whatever be the temperature at which the experiment is made; the sulphuret of silver, therefore, never ceases to be decomposable by the current, and the great increase of conductibility, that it presents at high temperatures, when the positive electrode is of silver or of platinum, is merely due to the establishment of a direct metallic communication between the two electrodes. The sub-sulphuret of copper and the protosulphuret of tin present the same phenomena as the sulphuret of silver. M. Hittorff, in operating on the

* Faraday himself, in pointing out the fact that the simple elevation of temperature, arising from the passage of the current, was sufficient to increase the conductibility of sulphuret of silver, observed that there is formed at the positive electrode, a slight deposit (of sulphur), which prevents the transmission of the current, and which can only be attributed to the electro-chemical decomposition of the sulphuret.

first of these sulphurets sheltered from contact with the air, has observed that its conductibility increased rapidly in proportion as its temperature was raised; and he recognised that when the current has traversed it for a certain time, there is some free copper at the negative electrode, and that the sulphur liberated at the positive, has caused the sub-sulphuret to pass into the state of mono-sulphuret. The formation of this mono-sulphuret, which is a conductor, and the manner in which the copper is deposited upon the negative electrode in slender filaments, which advance towards the positive, notably diminish the length of the column of sulphuret, really traversed by the current, and explain the considerable increase of conductibility that is manifested, and that is destroyed only in part, when we return to the ordinary temperature.

M. Beetz, on his part, has proved, as M. Hittorff had done for sulphuret of silver, that the bi-iodide of mercury is decomposed by the current, as soon as it is capable of transmitting it. With this view, after having purified this compound by a double sublimation, he introduced it into a glass tube which he had dried, and the two ends of which he had closed at the lamp, after having introduced into it two platinum wires, in order to place the bi-iodide in the circuit, in which he had also placed a galvanometer, having a single needle that was not very sensitive, and a voltameter charged with a salt of silver. The bi-iodide was heated in a sand-bath; at 212°, it began to become a conductor. At the same time that it acquired the yellow colour, and experienced a commencement of fusion, traces of decomposition became sensible by the property, which the platinum electrodes acquire of themselves, giving rise to a current, — a property termed polarisation, and of which we shall speak in the following paragraph. The bi-iodide having become altogether liquid, M. Beetz caused a current to pass through it for fourteen hours, taking care to maintain the same temperature; during the whole of this time, the needle of the galvanometer maintained the same deviation, and at the termination of this experiment, 0·162 grs. of silver were found reduced in the

voltameter. However, the tube that contained the bi-iodide having been broken, no trace of mercury was perceived at the negative wire; but the mass had become black around the positive wire; and upon throwing some fragments of it upon paper impregnated with starch, the appearance was manifested of the violet colour, which indicated the presence of pure iodine, whilst proto-ioduret was found at the negative electrode. It was a difficult matter to determine accurately the proportion of iodine liberated; however, M. Beetz was enabled to judge approximately that it was lower than what it ought to have been according to the quantity of silver reduced in the voltameter; which is probably due to the fact, that a part of the iodine recombines with the proto-iodide that always exists mixed with the bi-iodide, and even with that which is produced by electrolysis. The fluoride of lead had been also quoted by Faraday as an example of compound bodies, that may become very good conductors by simple elevation of temperature, even before being melted, and without undergoing decomposition. M. Beetz has proved in a positive manner, that this compound is electrolysed as soon as the current traverses it. Indeed, the platinum plates, that are employed to place it in the circuit, are polarised as with the bi-iodide; and, in proportion as it enters into fusion, bubbles of colourless gas are seen to be given off at the positive electrode, which is at the same time powerfully attacked, and a greyish mass, which is an alloy of lead and platinum, is formed at the negative. The needle of the galvanometer, that is placed in the circuit, retains the same deviation during the whole time that the electrolysation of the fluoride is going on; and the quantity of silver, reduced in the voltameter, compared with the weight of lead obtained, indicates that the fluoride of lead obeys the law of electrochemical equivalents.

We have already mentioned in the First Chapter, the property possessed by glass of becoming a conductor, when heated. M. Beetz assured himself, in operating on glasses of different qualities, and especially on Fuchs' soluble glass, that they become conductors between 392° and 428°, and that the platinum

wires, by means of which they are placed in the circuit, are powerfully polarised, which proves the existence of electrolysis. We shall see hereafter still more direct proof of this decomposition in the use M. Buff has made of melted glass as a liquid conductor interposed between the pairs of a pile.

But of all the anomalies, that are presented by the phenomena of electrolysis, those which have most attracted the attention of philosophers, and which at first sight have presented the greatest appearance of escaping the general laws, that regulate this mode of action, is the inequality respectively in the production of the elements, which are transported to the two electrodes, that, in many cases at least, the two portions of the electrolyte, in which each of the electrodes are plunged, seem to possess. MM. Daniell and Miller were the first who observed, by employing the apparatus composed of two cells, separated by a membrane, and filled one with acidulated water, the other with a solution of sulphate of copper, or sulphate of zinc, that when the positive electrode plunges into the solution of sulphate, and the negative into acidulated water, oxygen and hydrogen are alone obtained as the products of decomposition; whilst, on changing the place of the electrodes, oxygen is obtained at the positive electrode, and metal at the negative; in both cases, one equivalent of sulphuric acid is found with the oxygen at the positive electrode. If the two cells are equally filled with sulphate of copper or of zinc, we can easily prove, by analysing after the experiment the liquids contained in each cell, that all the copper or zinc, deposited at the negative electrode, arises only from the sulphate contained in the cell into which this electrode is plunged.

Among the experiments of Daniell and Miller we will in addition quote those, in which sulphate of potash and sulphate of magnesia, having been placed successively in the positive cell, only $\frac{1}{5}$ of an equivalent of potassium, and $\frac{1}{12}$ of that of magnesium are obtained. Alumina, magnesia, or oxide of copper do not render themselves in any proportions at the negative electrode, plunged in an acid solution, when they form with potash a double sulphate, the solu-

tion of which is placed in communication with the positive electrode.

In all the phenomena that we have been describing, the membrane, by which the vessel is divided into two compartments, has no influence over the results; so that its place may be supplied by a simple syphon tube filled with liquid, by which communication is established between the two compartments, positive and negative. It was by employing an analogous mode of communication, that M. Pouillet operated, when he found an anomaly of the same kind, as those which we have been describing, in the decomposition of chloride of gold. He placed the solution of this chloride in a series of U tubes, the lower parts of which being narrower, did not allow of the liquids, with which the two parallel branches were filled, mixing easily (*Fig.* 237.). On uniting the liquid columns of the to successive tubes by platinum wires, and causing the extreme columns communicate, the one with the positive electrode, the other with the negative, he has remarked that, when the current had passed for a certain time, all the negative branches of the tubes were less coloured than the positive, that gold was deposited at the negative wire without any trace of the liberation of hydrogen, and that chlorine was liberated without oxygen around the positive wire. It was easy to prove that, whilst the liquid of the positive branch contained as much chloride of gold as at the beginning of the experiment, that of the negative branch had lost a quantity precisely corresponding to the weight of the gold deposited. It would seem to follow from this, that the decomposing power belongs exclusively to the negative electrode.

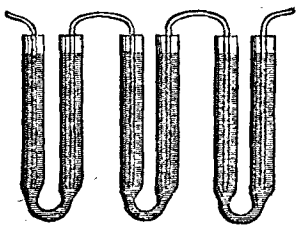

Fig. 237.

M. Hittorff arrived at a still more general result, by showing that the proportion of metal, reduced by electrolysation, which is furnished respectively by the part of the liquid in contact with the negative electrode and by that, in which the

positive is plunged, remains the same for a same solution, whatever may be the force of the current, but varies with the nature and degree of concentration of this solution. The apparatus that he employed, like that of Daniell's, is composed of a cylindrical glass vessel, separated into two compartments, not by a porous diaphragm, but by a disc of glass of a diameter less than that of the vessel; so that there remains between the edge of this disc and the inner side of the vessel a liquid stratum, which the current is able to traverse. The whole vessel is filled with the same solution, the positive electrode plunging into one of the compartments, and the negative into the other; the apparatus is so arranged that it may be separated into two pieces, corresponding to the two compartments, and by means of a glass plate that may be introduced between them, it is easy to preserve the liquids contained in each without their mixing. The cylindrical vessel is placed vertically; the positive electrode lodged in its lower part, is in each case made of the same metal that serves as the base of the salt submitted to electrolysation; the negative is of silver, and has the form of a little cone, the summit of which is upward, in order the better to retain the metallic deposit. After each experiment, this deposit is weighed; the weight of metal lost by the portion of liquid contained in the negative compartment is then determined; this second weight is deducted from the former, which gives the quantity of metal furnished by the positive compartment, that has been transported from the positive electrode to the negative. The relation between this quantity and the total quantity of metal deposited, indicates the proportion of metal transported.

The following, then, are the results obtained with solutions of copper, of various degrees of density: —

Density of the Solution.	Quantity of Sulphate of Copper in respect to Water.	Proportion of Copper transported.
1·0521	1 sulph. cop. to 6·35 water.	27·6 per cent.
1·0553	1 „ 18·08 „	34·5 „
1·0254	1 „ 39·67 „	35 „

He operated in the same manner upon solutions of acetate, nitrate, and sulphate of silver, and found at the end of a great number of experiments made with much care, that the proportion transported from the negative electrode to the positive was for

The acetate	- - - -	62·6 per cent.
The sulphate	- - - -	44·6 „
The nitrate	- - - -	47·4 „

It is to be remarked that, although the absolute quantities were sometimes very different from one experiment to the other, the relations varied very little from those indicated above, which are the means of the results obtained for each salt. The duration of the experiment was not always the same; but there resulted no appreciable change in the value of the relations found. When the metal, in its deposite at the negative electrode, is accompanied by a liberation of hydrogen, we may be certain that a part at least of this metal is in a state of oxide: M. Hittorff verified this by employing for an electrolyte a very neutral solution of sulphate of iron: the weight of iron deposited at the negative electrode is found superior to that which should be the result, in virtue of the law of the equivalents of the decomposition of nitrate of silver, placed in the same circuit; indeed, on precipitating the deposite of iron by ammonia, after having dissolved it in aqua regia, which weighed 21·043 grs., it is found that iron properly so called entered into this weight only as 14·737 grs., a number very little different from 14·729 grs. calculated according to the equivalent of silver, deposited by the same current.

A still more important fact to notice is that, when nitrate of silver is dissolved in alcohol, instead of being in water, which renders it a much worse conductor, and causes the operation to last a much longer time, only 43 per cent. of silver is found transported from the positive electrode to the negative, instead of 47 per cent.

The various facts, that we just related, do not, in our opinion, prove any difference of power in the poles, as M.

Pouillet thinks, nor, as MM. Daniell and Hittorff seem to presume, a faculty of transport variable with the nature of the combination, subjected to electrolysation, and dependent to a certain point upon the affinity, by which these elements are united. They are merely the effect of the non-homogeneity of the liquids submitted to experiment; whence it arises that the current not only decomposes the salt dissolved, but decomposes also the more or less acidulated water, that is found in the solution. M. d'Almeida has, indeed, shown that, in the electrolysation of a dissolved salt, the deposite of metal, — of copper, for example, — at the negative electrode, may arise from two sources; either from the direct electrolysis of the salt, or from a secondary action, namely, the reduction brought about by means of the nascent hydrogen, due to the decomposition of the water. If the solution is perfectly neutral, and especially if it remains neutral during the whole course of the experiment, the metal deposited at the negative electrode, arises almost entirely from the direct decomposition of the salt; if the solution is acidulated, the nascent hydrogen is the principal cause of the reduction of the salt.

M. d'Almeida has verified the accuracy of his general rule by operating upon solutions of nitrate of silver and of copper, sulphate of copper, of silver, and of zinc; only there is a very great difficulty in maintaining a solution neutral, during the whole continuance of the electrolysis. The solution submitted to experiment, for example,—a neutral solution of nitrate of silver,—is placed in two distinct vessels, which communicate together by a very small opening, as in M. Pouillet's tubes (*fig.* 237.). In one of the vessels is plunged a plate of platinum, serving as the negative electrode; in the other a plate of silver, which is the positive electrode. The current passes for twenty-eight hours; at the end of that time, 2·156 grs. of silver is found deposited at the negative electrode; and analysis shows that 1·124 grs. of these 2·156 grs. arise from the solution that surrounds the electrode, and 1·032 grs. from the other vessel; in this case, the solution is as neutral as possible, and it is kept in this state by the positive silver

electrode, which combines in proportion as the nitric acid is carried to it. If the solution is slightly acid, we find that the 2·156 grs. deposited at the negative electrode, have been entirely taken from the solution placed in the vessel in which this electrode was plunged. It is evident that, in the former case, the decomposition of the nitrate of silver is brought about almost entirely by the way of electrolysis; since, as should take place by this mode, according to Grotthus's theory, the elements deposited at the two electrodes have been furnished equally by the parts of the solution in contact with each of them. In the latter case, on the contrary, the acidulated water that is in the solution being more conducteous than the nitrate, it is that which is decomposed; and its nascent hydrogen produces the reduction of the salt at the negative electrode, which is the cause of the reduced metal being furnished only by the liquid in contact with that electrode. M. d'Almeida, indeed, satisfied himself in a direct manner that the acidulated water, as it is found in the solution of the nitrate, conducted the electric current better than this solution in a state of neutrality.

The same thing takes place in all the experiments, that we have quoted in this paragraph, and especially in those of M. Pouillet and of M. Hittorff. Thus, in the former, it is the hydrochloric acid, that is always found in the solution of chloride of gold, which is decomposed rather than the chloride, which is a worse conductor; chlorine is liberated at the positive electrode, and the gold of the chloride that surrounds the negative electrode is reduced by the nascent hydrogen. There results from this reduction the constant formation of hydrochloric acid, which thus supplies the place of what is decomposed.

In M. Hittorff's experiments the effects observed are mixed; a part of the reduced metal is derived from the direct electrolysis of the salt, and the other from the reduction by hydrogen, due to the decomposition of the acid water contained in the solutions of the metallic salts, which are so rarely and with so much difficulty neutral. What proves the accuracy of this explanation is, that the more diluted the

solution of copper is, the greater becomes the proportion of copper reduced directly to electrolysis; because the strength of the acidulated water is diminished. It is by no means certain that, although the positive electrode may be of copper in a salt of copper, and of silver in a salt of silver, that the acid accumulated around this electrode is all neutralised by the metal; it is, on the contrary, probable that some remains in the solution in the free state; and then it is the acidulated water that is decomposed, and its hydrogen contributes in part to the reduction of the metal. Indeed, as is proved by the numerical results recorded above, the proportion of sulphate of silver decomposed by direct electrolysis is less than that of nitrate, which is almost entirely decomposed in this manner; because the sulphuric acid, liberated at the positive electrode, escapes in a greater quantity than the nitric, from combination with the silver. The only very singular fact is that, with acetate of silver, the proportion of silver, furnished by the positive compartment, is more considerable than that which is furnished by the negative itself. It is probable that there is here some mixture of the liquids contained in the two compartments; that, in particular, there passes from the positive electrode to the negative a small quantity, which thus increases the proportion of the salt of silver, that is found in the negative compartment. This mixture must arise essentially from the difference of density of the liquids, and perhaps also from a mechanical transport, which occurs in a sensible manner only when the liquid is an imperfect conductor, which is the case here, and which causes the experiment to last twice as long as with solutions of nitrate and sulphate. Moreover, this double origin of the metal, deposited at the negative electrode, in the electrolysis of salts, is recognised in the appearance itself of the deposit, which is very different, according as the metal arises from electrolysis or from reduction by hydrogen. This is easily to be proved, by making use of solutions more or less acid, and more or less exhausted of sulphate of copper and of nitrate of silver. Thus Mr. Smee saw, on decomposing sulphate of copper, by means of a current of two pairs, the

first deposit of copper to be brilliant, united, and ductile; this it is which arose exclusively from electrolysation. The second was a little brittle; it is because there was already a little mixture of copper, arising from electrolysis and of that reduced by hydrogen. Finally, the third was like sand; then spongy; there was scarcely anything besides copper reduced by hydrogen; and at last the gaseous hydrogen finished by appearing. The liquor evidently contained scarcely any more sulphate, and was become too acid, and yet the positive electrode was of copper. We shall return to this subject, and especially to Mr. Smee's work, when engaged with the metallurgic applications of electricity, for which these questions possess great importance, as may be understood from the example of copper that we have just given.

However, we will remark further that the explanation, by which M. d'Almeida accounts so well for this apparent inequality of electrolysation around the two electrodes, is equally applicable, as he has himself observed, to the case of alkaline and earthy salts as it is to that of metallic salts, and that it finds in this fact a remarkable confirmation. Thus, if after having poured equal quantities of nitrate of potash into the two vessels of the preceding experiments, he renders the solution acid into which the positive electrode plunges, he finds that, after the decomposition, there has been only a feeble proportion of this part of the solution decomposed, the current having passed by preference through the acidulated water; it is, on the contrary, in the negative vessel that the decomposition of the salt has been the most feeble, if the solution of this vessel has been rendered strongly alkaline. Now, what is done artificially is brought about naturally by the electrolysis itself of the salt, which renders the positive solution acid, and the negative alkaline; but as, in general, the acid of dissolved salts (nitrates, sulphates) is a much better conductor than their bases, soda, potash, &c., it follows that the salt should undergo — and it does actually undergo—a less abundant decomposition in the parts of the solution in which the positive electrode is, which is that wherein the acid is liberated. But if

the salt remains neutral during the whole continuance of the experiment, the positive and negative solutions furnish equally their part toward the electrolysing action. In order to obtain this neutrality, M. d'Almeida, if he was operating, for example, upon sulphate of potash, poured beforehand some potash into the positive vessel, and some sulphuric acid in equivalent quantity into the negative, with equal volumes of saline solution; he then allowed the decomposition to continue until the quantities of acid and of base, introduced at the outset, were in excess on the opposite sides to those into which they had been poured. By this process each of the sections is alkaline for the half of the experiment, and acid during the other half. The influence of the acid and of the alkali is therefore equally exercised on both sides at the moment when the decomposition is stopped; it is as if the solution had remained neutral all the time.

It would be useless now to return to the numerous experiments made by Daniell and Miller, with the diaphragm apparatus upon the decompositions of earthy and alkaline salts, the phosphates in particular. We shall confine ourselves to remarking that they are all favourable to the theory, that we have given upon the composition of salts, and in particular to that of Graham on the phosphates, in which he considers water to play the part of a base; and with respect to the different proportions furnished by the two compartments in the products of electrolysis, the explanation of M. d'Almeida is perfectly well applicable.

The study that we have been making of the forms, so various and sometimes apparently so complex, under which electro-chemical decomposition is presented, at the same time that they enable us to trace these forms to the simple laws of Davy and of Faraday, no less point out to us the difficulty there is in discovering these laws in the midst of so many causes of perturbation. Thus, it is necessary to guard against the action of these causes, in order to establish on solid bases the generality of the law of the definite action of the current, which has been denied by several philosophers. This has been done successively by M. Buff and M.

Soret, in researches conducted with remarkable care and precision.

M. Buff has especially in view to verify the accuracy of the electrolytic law in cases of very feeble currents, and consequently of very prolonged actions — cases in which decomposition is often hardly apparent, and in which consequently it requires much time in order to discover it and to appreciate its effect, which is the cause why several philosophers have not only contested the existence of the law, but even that of electrolysis, when the electricity transmitted does not attain to a certain degree of intensity. M. Buff's first object was to determine the relation of the electrolytic action to the force of the current.

The liquid submitted to decomposition was a neutral solution of nitrate of silver of perfect purity. Two plates of silver were plunged into it, so that, under the influence of the current, silver was detached from one, which passed and arranged itself at the other. He employed in these experiments a Daniell's pair, so as to preserve a force almost constant for several days. He caused the force of the current to vary by introducing into the circuit wires of variable length, which served at the same time as wires to galvanometer-multipliers, so that by means of the deviation produced upon the needles, the degree of constancy of the current might be determined. The wires were two in number; and according as they were placed in the circuit one after the other, or as one alone was there, or as both were arranged parallel to each other, three currents were obtained, the relative energy of which may be represented by 1, 2, and 4. The resistance of the wires was so great that the resistance of the pile, together with that of the decomposition trough, might be set at a small fraction. It follows from the table of experiments made to a great amount, that the weight of the deposit of silver was always proportional to the force and to the duration of the current. M. Buff also placed in the circuit of the constant pair two successive troughs, filled with the same solution of silver; the two resistance wires were adjusted end to end; the electrodes, to

the number of four, were thin plates of silver. The current remained in action, without interruption, for about nine days — namely, 12,539 minutes. At the end of this time, there were found: —

	In the 1st trough.	In the 2nd trough.
Loss of weight of the positive plate	4·111 grs.	4·121 grs.
Increase of the negative - -	4·105 „	4·117 „

The solution of silver contained ·385 grs. of neutral solution of nitrate of silver in ·061 cub. in.: a more diluted solution, which contained only ·154 grs. to ·061 cub. in. was placed in succession with the former. At the end of fifty-one and a half hours, the negative silver plate had increased in weight 1·919 grs. in the more concentrated solution, and 1·912 grs. in the more diluted. Thus the fact that, whether the solution be more or less diluted, it exercises no influence over the electrolytic law.

On substituting pure water for one of the solutions of silver, there was obtained, at the end of four days, or 5470 minutes, an increase of ·369 grs. at the negative plate, which plunges in the solution of silver, and a film of oxide of silver on the positive plate of silver plunged in the water, which, when carefully removed, indicated a loss of ·369 grs. in weight by this plate. Thus the effect of the electrolysation of water, even by very feeble currents, is similar to that of the electrolysation of the solution of silver; and yet we should have thought from appearances that the water was not decomposed. It is the same with water slightly acidulated with sulphuric acid.

Finally, the electrolysation of sulphate of copper presented to M. Buff a perfectly satisfactory agreement with that of the nitrate of silver, provided the solution was perfectly pure, and deprived of all excess of acid. It is, therefore, well established by M. Buff's experiments, that it may be proved that even the most feeble currents, if their action is sufficiently prolonged, decompose electrolytic liquids, according to Faraday's law of definite action; and that it does not appear that they traverse these liquids, even in the smallest proportion, without decomposing them.

Upon salts of copper, both pure or mixed with others, M. Soret has also verified Faraday's law. He began by preparing these salts, so as to have them as pure and as neutral as possible, by a series of successive crystallisations and solutions. He produced his decompositions by placing his solutions in tubes, and by using for electrodes wires of platinum from ·0154 to ·0231 in. in diameter. His current was produced by Bunsen's piles, of from two to five pairs feebly charged. When he considered that the action had been sufficiently prolonged, he removed the electrodes covered with copper, plunged them for a certain time in distilled water, in order to wash them, then dried them rapidly with blotting paper, and weighed them; he then dissolved the deposit of copper in nitric acid, and again weighed the platinum wires, in order to obtain the weight of copper deposited. It is necessary, in order to obtain good results, that the deposit of copper should be united and compact, otherwise there is a risk lest a portion of the copper may not be detached, or not oxidised. M. Soret found no advantage in employing copper, instead of platinum, for the positive electrode; the solution of this copper not occurring always in a normal manner, and delicate experiments not having pointed out to him any sensible differences in the quantity of copper deposited, according as the solution was neutral or acid.* Indeed, three experiments furnish the following results: —

* M. Jacobi, as the result of numerous experiments, and by employing copper electrodes, had given up employing the decomposition of sulphate of copper, for determining the intensity of the current, on account of the numerous anomalies, that had been presented to him by this decomposition. Thus, on comparing together the weights of copper lost on one side and reduced on the other, he found, in a series of experiments, 7·4962 of copper lost for 7·1743 of copper reduced, which makes a difference of 4·5 per cent. M. Jacobi recognised himself that this anomaly is due to the experiments having been made with the sulphate of copper of commerce, which is not pure; this explanation is found amply justified by the results obtained by M. Soret on employing sulphate of copper chemically pure. Indeed, in this case, it is of little importance whether the solution becomes acid or remains neutral, the quantity of copper deposited upon the negative electrode necessarily remaining the same for the same current, whether it arises from direct electrolysis or from reduction by hydrogen.

Weight of Copper deposited in Sulphate of Copper.			Differences.
	Neutral.	Acid.	
1st Exp.	−2·5685 grs.	2·5700 grs.	+0·0015
2nd „	−2·0897 „	2·0927 „	+0·0030
3rd „	−5·1895 „	5·1926 „	+0·0031

After having verified, by numerous trials, that, under identical circumstances, two perfectly similar solutions of sulphate of copper give deposits, equal within three or four thousandths of a grain, he found that it was the same for two solutions, the one saturated, the other diluted. But if the two solutions, still being similar, are at different temperatures — the one at 68°, and the other at 212°, for example,— this latter gives a sensibly less deposit, which is due, as may be proved in a direct manner, to the dissolving action of sulphate of copper at 212°, even though neutral, upon metallic copper.

Nitrate, phosphate, and acetate of copper were placed, concurrently with sulphate, in the circuit; each of these solutions in each case gave the same deposit of copper at the negative electrode as the sulphate did. The differences in weights of from 1 to 3 grs., and even to 6 or 8 grs., were at a mean 0·003 grs., sometimes in one direction, sometimes in another, and never exceeded 0·006 grs., except in a single case, in which the difference rose to 0·009 grs. It was necessary not to prolong the action with the nitrate too much, so as to avoid liberating too much nitric acid, this acid soon exercising a dissolving action upon the copper deposited; and it is necessary that the acetate be very concentrated, the deposit of copper, without this precaution, not being compact, and the differences being too great.

Sulphate of copper and sulphate of potash, mixed in equal volumes, form a solution, which gives the same deposit as pure sulphate of copper. The bichromate of potash mixed with sulphate of copper forms no deposit, but merely gives a liberation of gas. The mixture of sulphate of copper and borate of soda gives a deposit of copper, but this deposit is

always a little more considerable than those obtained simultaneously in pure sulphate of copper; and the differences are too great — ·046 to ·107 grs.— to be able to be attributed to errors of experiment. Moreover, the deposit is never compact; and it also appears a little oxidised, which it owes to its slightly spongeous form. The sulphate of protoxide of iron, mixed with sulphate of copper, sensibly diminishes the deposit of copper; which is due chiefly to the copper's dissolving to a maximum in the sulphate of iron, and in there being always formed a certain quantity of this sulphate, when the sulphate of the protoxide of iron is allowed to be exposed to the air, —a formation that must be facilitated by the liberation of oxygen and of free acid, that accompanies electrolysis. The sulphate of manganese produces the same effect as the sulphate of protoxide of iron. The nitrate of cobalt, the sulphates of zinc and of cadmium, in no way alter the weight of the deposit of copper; and no trace is found in this deposit, of cobalt, zinc or cadmium, which plainly proves that copper alone is deposited. The following is the Table of comparative results obtained by the passage of the same current in a saturated solution of sulphate of copper, serving as the term of comparison, and in another solution. (See Table on next page.)

We may therefore conclude, from these last experiments, that the law of electro-chemical equivalents is found to be justified within the limits of errors of observation; and that, if there is a proportion of electricity that traverses the liquid without producing decomposition, it can only be a very small fraction, $\frac{1}{500}$th at least, of this total quantity of electricity transmitted; indeed, if it were $\frac{1}{500}$th, or less, the differences that would result from it would be smaller than the errors of observation.

Influence of the Electrodes upon Electro-chemical Decomposition.

There exists yet another circumstance, which, independently of its proper and distinct effect, plays also an important

Name of the Solution compared with Sulphate of Copper.	Weight of Copper deposited in		Difference.
	Sulphate of Copper in Saturation.	The Solution inscribed in the 1st Column.	
	grs.	grs.	
Sulphate of Copper diluted by ½ its volume of water - -	5·2373	5·2466	+ 0·0092
Sulphate of Copper diluted by 1 volume of water - - -	2·7584	2·7522	— 0·0061
Sulphate of Copper diluted by 1 volume of water - - -	5·1261	5·1200	— 0·0061
Sulphate of Copper diluted by 1 volume of water - - -	3·9801	3·9848	+ 0·0046
Concentrated Nitrate of Copper -	4·3832	4·3817	— 0·0015
Concentrated Nitrate of Copper -	7·5480	7·5649	— 0·0030
Concentrated Nitrate of Copper -	1·9537	1·9445	— 0·0092
Phosphate of Copper dissolved in Phosphoric Acid - - -	2·7878	2·7940	+ 0·0061
Phosphate of Copper dissolved in Phosphoric Acid - - -	1·8642	1·8688	— 0·0046
Phosphate of Copper dissolved in Phosphoric Acid - - -	2·1453	2·1437	— 0·0015
Acetate of Copper - - -	1·3004	1·2929	— 0·0015
Acetate of Copper - - -	1·2464	1·2495	+ 0·0030
Mixture of Sulphate of Copper and Sulphate of Potash - -	3·1507	3·1492	— 0·0015
Mixture of Sulphate of Copper and Sulphate of Potash - -	1·8456	1·8518	+ 0·0061
Mixture of Sulphate of Copper and Nitrate of Cobalt - - -	1·3484	1·3720	— 0·0048
Mixture of Sulphate of Copper and Nitrate of Cobalt - -	1·2881	1·2896	+ 0·0015
Mixture of Sulphate of Copper and Sulphate of Zinc - -	2·0964	2·2477	+ 0·1513
Mixture of Sulphate of Copper and Sulphate of Zinc - - -	1·5584	1·5614	+ 0·0030
Mixture of Sulphate of Copper and Sulphate of Cadmium -	1·9769	1·9800	+ 0·0030

part in those which we have been enumerating — I would speak of the nature, the form, and the physical state of the electrodes, which establish communication between the poles of the pile and the liquid to be decomposed.

We have already seen that there always exists, in the passage

of the current from a solid conductor into a liquid, a resistance independent of the conductibility proper of the solid body and of the liquid. This resistance is manifested in a very decided manner, when a liquid conductor is separated into two parts by a thin plate of metal, or when two liquid conductors, placed in two distinct vessels, into which each of the electrodes are immersed, are connected by a metallic arc. On placing a galvanometer and a voltameter in the circuit, it is easy to prove that, the more the metal of which the plate or the metal arc is made is attackable by the liquids in contact with them, the less is the resistance. It also varies with the relative nature of the metal and of the liquids; even when the metal is not attackable by either of the liquids. Thus with platinum plates employed, whether as electrodes, or for establishing communications between two or several successive vessels, the resistance is much less with concentrated nitric acid than with hydrochloric, less with hydrochloric than with sulphuric; it is more considerable with diluted nitric acid than with concentrated, whilst it is the reverse with sulphuric acid: saline solutions, those of potash and ammonia, present almost the same resistance. The intensity of the current exercises an influence not only over the absolute resistance, but also over the relative resistance of two liquids; thus, when the current is powerful, the resistance to passage is less for hydrochloric acid than for nitric acid; it is the reverse when the current is feeble. In order to obtain full assurance that these differences depend upon variations in the resistances to passage, and not in the conductibility of the liquid, we make use of several glasses—four, for example,—filled with liquid; they are connected by arcs of platinum, whilst the platinum electrodes are immersed in the two extreme vessels. It is very curious to perceive that, on varying the number of glasses, and consequently that of the alternations or passages from a solid to a liquid conductor, and reciprocally, we are able to render the same system of metallic-liquid conductors more or less conductors at one time than at another, which is simply due to our modifying the general intensity of the current, by a variation in the number of alternations. Such is the case, as we have said

with hydrochloric and with nitric acids. Thus, in making of these two acids, two perfectly similar systems, each communicating with one of the wires of a differential galvanometer, there is found, on compelling the current to divide itself between them, 48° in favour of the hydrochloric acid, when there is only one alternation; and 15° in favour of the nitric acid when there are five. But, in the former case, the intensity of the current transmitted by one of the systems alone was 75°, in the latter 30°. The same result is obtained with two platinum electrodes, employed either in nitric acid or in hydrochloric; and by causing the intensity of the current to vary by means of a pile of greater or less force.

The resistance to passage diminishes with the increase of the surface of contact of the liquid and the solid conductors; but it is proved that the greatest intensity of the current, which results from he increase of the surface of contact, increases in a greater relation than the surface itself when the current is feeble, and in a less relation when the current possesses a certain degree of intensity,—this degree being dependant on the relative nature of the solid and liquid conductors.

Before entering further into this order of phenomena, it is necessary to seek after the cause. Now, it is entirely in the chemical decomposition brought about by the current upon this liquid in contact with the solid conductor that it has its origin. In order to have a good representation of this part played by the electrode in electrolysis, we must have regard, as Faraday does, to the whole of the circuit, and to that power, of which we have already spoken, possessed by the current of transporting the force of affinity, that is ordinarily exercised at infinitely small distances. Now, their force originates at the electrodes, one of which attracts oxygen and the acid elements, and the other hydrogen and the basic elements.

Two circumstances may favour the exercise of the force, and consequently the passage of the current: viz., the facility possessed by the electrolyte itself of being decomposed, and the very affinity of the substance of which the electrode is

composed for that element of the electrolyte which the current tends to liberate upon its surface.* Thus, with electrodes of platinum, concentrated nitric acid will offer less resistance to the passage than dilute sulphuric or than hydrochloric acid, because it is more easily decomposed than the other two acids. But, on the other hand, as platinum has an affinity for chlorine, it may be that this circumstance outweighs the former, since experiment shows us that this takes place for a certain intensity of current. This effect is still much more sensible when we employ for positive electrodes oxidisable metals, such as iron, zinc, &c., and for negative electrodes, peroxides that have a great affinity for hydrogen, such as the peroxide of lead, with which the platinum plate may be covered. It is evident that the oxygen and hydrogen, for example, are attracted with much more force — the one in one direction, the other in the other, — when the action of the current is added to the affinity of the electrode. But the manner in which this influence of the nature of the electrodes is made most sensible is, in facilitating or in preventing the deposit, which is always in a greater or less degree formed upon the surface of each of them, and which is the most decided cause of the resistance to passage. Thus, it is easy to see, in the electrolysis of acidulated water with platinum electrodes, that there remains a thin film of oxygen adherent to the surface of the positive electrode, and a similar one of hydrogen to the surface of the negative electrode; these two films, by preventing the immediate contact of the electrodes with the liquid, lessen the facility of passage of the current, at the same time diminishing its intensity, as we shall see, by producing a secondary current, determined in a direction contrary to that of the principal current. It is no longer the same when the electrode, combining with the oxygen, forms a soluble oxide, or when, like the peroxide of lead, it absorbs the hydrogen, allowing of the combination of this gas with

* We are here speaking only of the passage of the current at the surface of contact of the electrode and the liquid, and not through the liquid itself, the latter passage depending upon the conductibility of the liquid, a property whose relation with electrolysation has not yet been determined.

one part of its own oxygen. With regard to the existence of these deposits, the nature of which varies with that of the electrolyte, it may be proved either directly or indirectly, by a peculiar property which they impart to the electrodes. Let us examine in succession these two modes of demonstrating their presence.

The attentive examination of the electrodes enables us very quickly to discover upon their surface, when they have been employed for electrolysis, the deposits, even the gaséous ones, that remain adhering to them. In this way we discover that even the most feeble current, such as that of a single pair, cannot traverse an electrolyte acidulated water, for example, without decomposing it. The gaseous deposit is sometimes so little apparent, even with the microscope, that, in order to render it sensible, it is necessary to place the apparatus in which the decomposition takes place, *in vacuo;* and then the bubbles of gas are seen to detach themselves from the surface of the platinum electrodes, and the galvanometer that is in the circuit suffers a greater deviation, a proof that the gaseous film was the cause of the resistance to passage. When the deposit is solid, it is an easier matter to see it; and it commonly forms, in consequence of its little thickness, very brilliant coloured films, analogous to the colours of thin plates. M. Nobili, who discovered them, and called them by the name of electro-chemical appearances, made a very particular study of them. In order to obtain them, he arranges horizontally a plate of platinum or of silver, or even of steel, at the bottom of a flat vessel. He covers it with a thin layer of an electrolytic solution. Then he plunges vertically into the liquid over the plate a fine point of platinum, so that it shall be only $\frac{1}{10}$th or $\frac{1}{20}$th of an inch in distance from this plate. The point and plate serve alternately as positive and negative electrodes. One of the most beautiful appearances is that which is obtained upon the positive electrode with acetate of lead. It is altogether similar to Newton's coloured rings and quite as brilliant; it is dúe to a very thin deposit of peroxide of lead, a substance which, like the acids, is transported to the positive pole. The

action must not be prolonged too much, nor must too powerful a current be employed, for fear that, the deposit becoming too thick, the colours should disappear. The appearances are in general more brilliant on the positive electrode; however, very decided ones may be obtained on the negative by employing a more energetic current, and mixing together two or three solutions. In order to have the power of more readily comparing the positive and negative appearances, it is well to produce them at the same time upon the same plate. Nobili did this by arranging above the plate A B, two fine platinum wires, each communicating with one of the poles of the pile N P (*fig.* 238.). The current came out from the point P, pene-

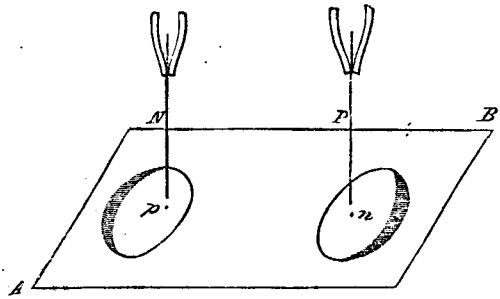

Fig. 238.

trated into the plate at *n*, then came out from the plate at *p*, beneath the second point N, into which it entered in order to complete its circuit. The result was the production of a negative appearance at *n*, and a positive one at *p*. But if these appearances were produced so as to be too near to each other, they were frequently deformed, as if they were mutually repelled, and expanded exteriorly. This deformity ceased to take place as soon as a thin screen of glass was placed between the two points, so as to prevent all direct communication between the two parts of the liquid that cover the portions of the plate upon which the appearances are formed. It was, therefore, evidently due to this,—that, when there was no glass screen, it happened that, among these currents which disseminate in filaments throughout the liquid between the two points that serve as poles, those which should

have formed the interior contour of the coloured rings traversed directly from one point to the other in the liquid exclusively, instead of passing in a part of their course through the plate, and this on account of the resistance to passage that it offers to them. It is not the same for the exterior filaments, which would have a longer course to take through the liquid; thus they traverse the plate because, notwithstanding the resistance to passage, this second path offers to them a more easy transmission. When the screen is there, there is no longer a choice, and all the currents are almost compelled to pass through the plate, which causes the appearance to be no longer deformed. We see by this example that the form and position of the electro-chemical appearances may serve, in a very useful manner, to follow this mode of the propagation of currents in a liquid.

Returning to the appearances themselves, we shall add that, among the most beautiful are found those which are obtained at the positive electrode, on decomposing animal or vegetable organic substances, which induced Nobili to see in this the cause of the colouration of plants, and particularly of flowers. With regard to the deposits that arise from the electrolysis of inorganic compounds, they have been the subject of a profound examination, not only on the part of Nobili, but also on the part of M. Becquerel. We shall have occasion to return to the results obtained by these two skilful physicists, when engaged upon the chemical applications of electricity. It would be useless in this place to enter into further details, for it is easy to conceive the innumerable variety of effects that may be obtained by employing different solutions, either pure or mixed, by raising or lowering their temperature, by producing the deposits upon plates, susceptible or not of being attacked by the elements liberated. We may simply add that the production of electro-chemical appearances has been the subject of an experimental and theoretical study, both on the part of M. E. Becquerel, who thought that it was subject to a very simple law, analogous to that which governs Newton's coloured rings, as well as on the part of MM. Dubois-Reymond, and Beetz, who have

demonstrated that the phenomenon was more complex, and that it depended besides on several circumstances connected with Ohm's laws.

Let us now pass on to the indirect mode, by which the presence of the deposits is indicated. It consists in the property that they impart to the electrodes of giving rise to an electric current, by acquiring what is called secondary polarity; for example, two platinum plates that have been employed — one as positive electrode, the other as negative — in acidulated water, become capable of forming a voltaic pair, in which the former plate plays the part of the negative metal, such as copper or platinum, and the latter that of the positive metal, as zinc. This couple produces a current, that acts upon the galvanometer and upon the chemical or calorific voltameters: it is true that it is never very strong, and that its action has only a very short duration. When the principal current has traversed several homogeneous diaphragms or arcs, employed for connecting several liquid compartments one with the other, the secondary polarities, that are acquired by these diaphragms or arcs, make of them a veritable pile, named a *secondary pile*, and the action also of which never has a long duration. It is not necessary, in order to the establishment of the current, that the liquid conductor in which the polarised metals are plunged should be the same as that whose electrolysation has polarised them— a proof that this current does indeed arise from the metals, and consequently from the deposits, which have taken place on their surface. The same results are obtained, and with even a more decided degree of intensity, by the decomposition of saline solutions. All these secondary currents are due to the chemical reaction of the liquid, in which the plates are plunged, upon the deposits with which their surfaces are covered; and what proves this is, that the same effects are obtained by bringing about the deposits in a direct manner, instead of employing for this purpose the action of a current.* We shall study with care the formation of these

* For example, we have merely, as M. Matteucci was the first to remark, to place two very clean platinum plates, the one in oxygen, the other in hydrogen,

currents in the Chapter devoted to the production of electricity by chemical actions, of which they are a particular case. Let us simply remark further, that the polarisation, or rather the secondary polarities that are acquired by the electrodes, whenever they have transmitted dynamic electricity, however feeble or instantaneous it may be, are the most sensible indication of the formation of deposits on their surface, and consequently of the existence of electrolysis.

Is the resistance to passage simply due to the polarisation of the electrodes, or is it also due to the fact itself of the change of conductor? This question has been for a long time controverted. Fechner and Poggendorff have maintained that the two causes equally contribute to the phenomenon, against Ohm, who was the first to establish that the simple fact of the passage of the current from the solid conductor into the liquid does not generate resistance, and that the latter is merely an effect of the polarisation of the metals. Fechner had actually demonstrated, by very accurate measurements, in his fine work published in 1831*, that, in a closed voltaic circuit, in which an electrolyte is included, but without intermediate plates, the total resistance is always greater than are the resistances of the metal and the liquid taken together, which proves the existence of the resistance to passage; but he had not examined the cause of this resistance, and he confined himself to pointing it out, as had been done by Marianini and myself, in indicating the circumstances that cause it to vary, such as the nature of the metals and of the liquids, and such also as the size of the metal surface immersed in the liquid and the force of the current—two influences which are in the inverse ratio to it. It is true that Fechner, replying more recently to Ohm's observations, had thought he was able to establish, by considerations deduced from the resistance to passage, which exists in the pile, changing with time, and from its increasing constantly in proportion as the intensity of the

in order to obtain a very decided current upon afterwards plunging the two plates into acidulated water.

* Maussbestimmungen über die Galwanische-Kette, Leipsig, 1831.

current diminishes, the conclusion that there exists, independently of the effect due to polarisation, a positive resistance for the current when it traverses conductors alternately liquid and solid. But this kind of argument is not conclusive; because the effect of the polarisation of the electrodes being essentially to create a contrary current to that which is transmitted, and by this to diminish the intensity of the latter, it would be necessary, in order accurately to appreciate the influence of this polarisation, to know the exact relation that exists between the secondary current, to which it gives rise, and the primitive current, which itself has produced it; and this relation is not known, or at least cannot be determined in a precise manner.

The only mode of resolving the question is to demonstrate that there is no resistance to passage when there is no polarisation of the electrodes. Now, in order to obtain this absence of all polarisation, still transmitting the current through the electrolyte, it is necessary to employ instantaneous currents, of equal intensity, sent alternately in contrary directions, and succeeding each other with sufficient rapidity for the polarisation determined by the first to be annulled by the inverse polarisation, that is produced by the following one; that, for example, oxygen and hydrogen, brought alternately by the electrolysis of water upon the metal surface, may succeed each other with sufficient rapidity to recombine, without being liberated in the gaseous state or remaining adhering to the metal.

I was the first to point out a fact, which indicated the possibility of this neutralisation of polarisation, by employing the alternate induction currents, produced by a Saxton's machine, and by transmitting them through an acid solution placed in the circuit by means of two platinum plates of a surface equal to that of the section of the liquid, which was itself placed in a primitive trough with a section of ·62 sq. in. and 3·93 in. in length. Not only was no gaseous liberation manifested upon the electrodes, but, on placing a platinum plate as a diaphragm at the middle of the liquid, the intensity of the transmitted currents was not diminished;

and although this plate received successively upon each of its faces the oxygen and hydrogen arising from the decomposition of the water, no gas was seen to appear. The intensity of the currents was measured by a calorific voltameter placed in the circuit, or the helix of a Breguet's* thermometer, or a fine platinum wire, which traversed the bulb of an air thermoscope.

Poggendorff and Vorsellmann de Heer, on repeating and varying my experiments, had arrived at contradictory results — the former having thought he had found a resistance to passage, independent of the polarisation of the electrodes; and the latter having observed it to disappear as soon as this polarisation ceased to exist. Both of them employed induction currents produced by Saxton's machine. M. Poggendorff measured the intensity of the currents, by means of two air thermometers, the bulb of which, being larger in one than in the other, was traversed by a fine platinum wire; he placed a metallic diaphragm in the middle of a rectangular box filled with the conducting liquid, so that the two parts of the liquid, separated by the diaphragm, could not communicate together; finally, he measured the resistance which the current suffered by the interposition of the diaphragm, by comparing it with that of a German silver wire ·007 in. in diameter. We may add, that M. Poggendorff was careful to turn the Saxton machine at all times with the same velocity, so as to have fifteen alternate currents per second. A great number of experiments, made with platinum, copper, and iron plates, placed in the same circumstances, sometimes in dilute sulphuric acid, at other times in a solution of hydrochlorate of soda, gave him for platinum a resistance more than double that for copper, and more than quadruple that for iron. M. Poggendorff remarked that, independently of the nature of the liquid and of the metal, the state of the surface of the latter influences in a very notable manner the resistance to passage, as well as did elevation of temperature, which diminishes it in a very considerable quantity. This diminution

* Vol. I. *fig.* 21.

must not be confounded with that, which is produced by heat in the resistance of conductibility of the liquid itself, which, as Ohm has demonstrated, is independent of the electrodes. Thus, with a diaphragm of platinum in diluted sulphuric acid at the temperature of 62°86, the calorific voltameter rose 74 divisions; and it rose about 110 divisions when the temperature of the liquid was raised to from 167° to 194°. If the temperature of the metal is raised to red heat, as in Leidenfrost's well-known experiment, then no current is transmitted — a proof that there is no contact between the liquid and the metal.

M. Vorsellmann de Heer, in order to show that the resistance to passage is due to the polarisation of the electrodes, employed two galvanometers, one of which, the least sensitive, measured the direct current transmitted; and the other, the more delicate, the current arising from the polarisation of the electrodes. Now, the intensity of one of these two currents was the inverse of that of the other — a proof therefore that the polarisation was the cause that diminished the principal current, and that produced consequently the resistance to passage. M. Vorsellmann employed only a single instantaneous current, always of the same intensity—namely, that which was produced by a semi-revolution of the armature of a Saxton's machine — a circumstance that enabled him to employ the magnetic galvanometer for measuring it. The electrodes were plates of platinum, of copper, or of iron, very homogeneous; and the liquid water acidulated by a little sulphuric acid.

Lenz, who in like manner employed only a single instantaneous current, had always found a resistance to passage, which is not astonishing, since he in this manner always brought about a polarisation of the electrodes. When we desire to demonstrate that there is no resistance to passage properly so called, we must succeed in nullifying it, by removing the causes that give rise to it, or at least in attenuating it, by diminishing the effect of these causes. I succeeded in accomplishing this before even the researches of MM. Poggendorff and Vorsellmann de Heer, by using, in place of in-

stantaneous or of a continuous current, a series of currents determined alternately in contrary directions. I produced these currents, not only by means of Saxton's induction apparatus, but also by rendering the currents produced by a Daniell's pile of ten pairs instantaneous and alternate, by means of one of the rheotomes or commutators, that I have described in the first volume.* I first satisfied myself, by placing in the circuit a capsule of platinum, containing a layer of concentrated nitric acid $\frac{1}{2}$ or $\frac{3}{4}$ in. in thickness, the upper surface of which was in contact with a disc also of platinum, that the discontinuous and alternate currents were conducted as well, whether they traversed the layer of nitric acid, or whether, by putting into contact the platinum capsule and disc, they were not compelled to traverse this layer. It was no longer the same when the currents were guided all in the same direction — a proof that the diminution of intensity, which they suffered in this latter case, was due to the polarisation of the two surfaces of platinum. The calorific voltameter that I employed in this experiment was not very sensitive; it is the one founded on the measure of the dilatation experienced by a platinum wire that is traversed by the current.† With this same voltameter and two platinum plates of 7·59 sq. in. of surface, plunged at a distance of ·39 in. from each other in sulphuric acid diluted with nine times its volume of water, I proved that, when the current was continuous and gas was liberated upon the two plates, the instrument went from 0° to 17°, and that it went to 20°, as soon as the communicator placed in the circuit was put in motion, and the current was thus rendered discontinuous and alternate. On the other hand, if, by substituting in the circuit for the liquid conductor a platinum wire of a resistance almost equal, so that the voltameter went from 0° to 20° by the effect of the continuous current, I rendered this current discontinuous and alternate, the instrument indicated no more than 17°. Thus this latter form diminishes in fact

* Vol. I. pp. 295. 398.
† Vol. I. p. 32. *fig.* 19.

the effect of the current; and if it increases it, when there is a liquid conductor in the circuit, it is because it annuls or diminishes the resistance to passage. The following also are the results of experiments made with diaphragms of different metals, placed vertically in a glass trough 6 in. in length, and 1 in. in width and depth, so as to divide the liquid conductor (sulphuric acid diluted with nine times its volume of water), into two, three, or four compartments, without any direct communication between them; the liquid was placed in the circuit, by means of two platinum plates inserted at the ends of the trough. The calorific voltameter is in this case an air thermoscope, the bulb of which, placed at the top of the tube, is traversed by a fine platinum wire; it carries an arbitrary division in millimetres ($\frac{1}{25}$ in.), which goes from the bottom upward.

	Continuous Current.	Alternate Current.
With a *platinum* diaphragm - -	68mm	54mm
Without diaphragm. - - - -	48	48
Difference -	20	6
With three *copper* diaphragms - -	144	128
Without diaphragm - - - -	133	126
Difference -	11	2
With three *tin* diaphragms - - -	127	106
Without diaphragm - - - -	115	106
Difference -	12	0

Thus, for each kind of diaphragm, the resistance to passage is much less with alternate currents than with direct currents, and it ends by becoming null with diaphragms of tin. We may also annihilate it with copper diaphragms when the latter have already served for several similar experiments, their surfaces then presenting a pulverulent aspect, which indicates that they have undergone a series of oxidations and of reductions. We succeed in rendering it almost insensible with diaphragms of platinum by employing a solution of hydrochlorate of ammonia, which causes the platinum to be alternately attacked and reduced by hydrochloric acid. We obtain the same result with dilute sulphuric acid, when we

employ for electrodes, the capsule and plate of platinum of which I have made mention above. On interposing between this capsule and disc a capsule of lesser diameter, we in no way modify the intensity of the alternate currents, which are transmitted equally well, whether the capsule be there or not, and whether it be of platinum, of copper, or of tin. However, this result is obtained with the platinum capsule only when the experiment has continued for a sufficient time to modify its surface; whilst, with the other two, it takes place immediately.

In order to succeed well in these latter experiments, it is necessary to employ the Saxton's machine, because we can cause the currents, that are determined alternately in contrary directions, to succeed each other with greater rapidity. Thus, in my latter experiments there were at least 40 per second. In the first there were only 27; and it is not surprising that, in those of Poggendorff, where there were only 15, the resistance to passage had never been completely annihilated.

It is evident, from what has gone before, that the cause which produces resistance to the passage from a solid conductor into a liquid, is the deposit upon the metallic surface of the electrode of the foreign substance, arising from electrolysis, whether the resistance due to this deposit be only *passive*, by the effect of the inferior communication between the liquid and the metal; or be *active* also, by the creation of a contrary current, due to the polarisation of the metallic surfaces. In every case, in order to annihilate the resistance to passage, it is necessary to prevent the formation of the deposit, or to destroy it immediately it is formed. It is this that is accomplished with the alternate currents, which, succeeding each other very rapidly, carry successively oxygen and hydrogen upon the same surface in an interval of time sufficiently short for them to be able to combine before becoming liberated. However, the aspect of the metal surfaces, that have for some little time transmitted these currents shows that there has not been simply a deposit of oxygen, but an oxidation, immediately followed by a reduction by hy-

drogen. Platinum itself becomes at last covered by a black powder, which is finely divided platinum, the production of which can only be explained by a series of oxidations and reductions, which this metal must have undergone. We shall see that oxygen, in the nascent state, is usually able to become capable of combining directly with platinum.*

We do not always obtain the disappearance of the deposit with alternate currents, and we can sometimes obtain it with continuous currents. Thus, as an example of the former case, I will cite lead, which, employed as a diaphragm, is covered by alternate currents upon both its surfaces, with a coating of white oxide, which is not reduced, whilst this coating is formed upon a single surface alone, when the current is continuous; whence it follows that, contrary to what takes place with other diaphragms, the current is less weakened by the interposed plate of lead when it is continuous than when it is discontinuous and alternate. As an example of the second case, I will cite nitric acid, which, in contact with the negative platinum electrode, renders its resistance to passage almost null, by preventing upon the surface of platinum the deposit of hydrogen, which it absorbs in proportion as it is produced, becoming converted into nitrous acid. I will again cite the fact, which I have already pointed out in the First Chapter of this Fourth Part, that we have merely to heat or to shake the negative platinum electrode plunged in an acid solution, in order to attenuate notably the resistance to passage, even by a continuous current. M. Beetz satisfied himself by direct experiments that this heating and shaking diminish proportionally more the polarisation of the negative than that of the positive electrode, especially when the current has but little intensity,— a case, in which is easily manifested the preponderant influence of

* The formation of the black powder of platinum is also observed when a powerful current has been transmitted for a long time continuously through a voltameter with plates or wires of platinum, charged with sulphuric acid diluted with nine times its volume of water. This powder is deposited at the bottom of the vessel, and evidently arises from a series of oxidations and reductions which the surface of the negative electrode suffers, under the alternate influence of the oxygen dissolved in the liquid and of the hydrogen that is liberated.

the shaking and heating of the negative electrodes over the facility of the current's being transmitted.

The part played by platinum as an electrode is very remarkable; for, although it passes for being not oxidisable, we see it comport itself like the metals that are so, but in a feeble degree. Thus the black powder, that is formed upon the platinum wires, that have been employed for a long time as electrodes to alternate currents in a solution of nitric or sulphuric acid, indicates that these wires have undergone a series of oxidations and of reductions, which is further proved by the condition of their surface, when the powder has been removed which from polish, as it was, has become covered with roughness. Gold and palladium present the same phenomena as platinum, but more promptly: gold becomes covered with a greenish pellicle; palladium with a layer of bluish black. These layers are, in like manner, formed by the pure metal, but very divided; for the burnisher renders to them, as to the black powder of platinum, the metallic brilliancy; and when introduced into the explosive mixture, the three powders equally cause it to detonate: only it is necessary for that of gold to raise the temperature to 122°.

For wires of platinum, as for wires of gold, the quantity of gas liberated goes on diminishing, in proportion as the pulverulent layer is formed; and at the same time the current transmitted increases in intensity, as is shown by the indications of the calorific voltameters. Thus, with platinum wires in water, acidulated to a tenth, at the end of one minute, the helix of the voltameter * marked 27°, and the gas liberated was ·427 cub. in.; and at the end of seventeen minutes, the helix marked 40°, and the liberated gas was in all about 2·74 cub. in., and only ·061 cub. in. in the seventeenth minute. The wires were then entirely covered with the black powder, and the gaseous mixture detonated without leaving any residuum — a proof that the oxygen and hydrogen existed in it in the proportion, that forms water. With gold wires there is sometimes, after the

* Vol. I. *fig.* 21. p. 33.

detonation, a slight residuum of hydrogen, which rises from the gold being slightly oxidised; this fact explains why the currents pass a little more easily, as is proved by the indication of the helix of the voltameter, which at the end of ten minutes marks as much as 46°.

The condition of the surface of the platinum exercises an influence over its facility of being disaggregated. Wires 7 in., and even 13 in., in length, whether straight or coiled into a helix, are very quickly covered with the black powder when, being plunged into water with one-tenth sulphuric acid, they serve as electrodes to induction currents, that succeed each other at the rate of 40 per minute. The operation is much longer and more difficult for plates; and the gases recombine at their surfaces a long time before any traces of divided platinum are perceived. With spongy platinum serving as electrodes, there is never any gaseous liberation, and the temperature of the calorific voltameter placed in the circuit is higher; in general, this temperature attains its maximum in all cases as soon as there ceases to be a liberation of gas.* The heating of the liquid, which increases the intensity of the current, when the wires being no longer blackened, there is a production of gas, exercises almost no influence when, the black layer being formed, all gaseous liberation disappears.

The property that we have been recognising in platinum, of bringing about the combination of the gases arising from electrolysis, in proportion as they are liberated alternately upon its surface, must evidently be the same as that in virtue of which this metal causes the detonation, on being introduced into it, of a mixture of oxygen and hydrogen made in the proportions that constitute water, as was discovered by Doebereiner. We may remark, first, that the conditions, which render platinum susceptible of inflaming the detonating mixture, are the same as those, that favour its disaggregation in electrolysis,—namely, the absence from

* We must not confound the temperature of the calorific voltameter placed in the circuit with that of the liquid decomposed, which is altogether independent of it.

the surface of all foreign matter whatever, the roughness that it presents, &c. Faraday has even remarked, that the mere fact of having served as an electrode in an acid solution renders a platinum plate eminently fitted to bring about the combination of oxygen and hydrogen. This is not all; the proof that, in Doebereiner's experiment, there is a succession of alternate oxidations and reductions is, that a platinum wire, well cleaned and coiled into a helix, employed, instead of spongy platinum, for inflaming hydrogen in the air, soon acquires a greyish pulverulent surface, which is due to the disaggregation of the metal. In order to facilitate the operation, it is necessary slightly to heat the platinum wire, by letting it be traversed by an electric current of feeble intensity, and directing upon the helix a current of hydrogen mixed with atmospheric air, by means of a stop-cock with two openings. The same disaggregation is observed in a platinum wire, that has been used for Davy's aphlogistic lamp. We have merely then to coil into a helix a platinum wire $\frac{1}{100}$ in. in diameter, and to place it upon a spirit lamp, after having carefully washed it, first in nitric acid, then several times in distilled water, so as to have it dry and sheltered from dust. The lamp is lighted, so that the wire becomes red; and when it is red, the flame is extinguished: it then remains incandescent by the effect of the vapour of alcohol. If the experiment is allowed to continue for twenty-four and even forty-eight hours, the wire, which was perfectly smooth, presents, at the end of this time, a pulverulent surface, due to disaggregated platinum — a proof that the phenomenon of the aphlogistic lamp consists also of a series of oxidations and reductions, due to the alternate action of the oxygen of the air, and of the vapour of alcohol. I have greatly varied this experiment. I have employed very pure alcohol, wicks of amianthus instead of cotton wicks, and have always observed the same result. I have besides remarked, that the wires whose surface is thus disaggregated, are much superior to others for making the experiment of the aphlogistic lamp succeed.

The phenomena, that are presented by platinum, as well

in this case as in that of electrolysis, are altogether similar to those, which take place with other more or less oxidisable metals, such as gold, silver, and copper, when exposed to the action of the flame of a spirit lamp —phenomena, which Dr. Henry has so well studied. These metals, and especially copper, are very rapidly reduced to powder, by the succession of alternate oxidations and reductions which they undergo.*

Let us now return to phenomena of electrolysis properly so called, and see how the property, which we have been recognising in platinum, and studying, may account to us for the anomalies, that have induced several physicists to conceive that the laws, by which chemical decompositions are regulated were at fault, and consequently were not general.

I had made a series of experiments, in which I employed for electrodes plates and wires of platinum perfectly purified, but of different dimensions, and as an electrolytic liquid very pure sulphuric acid, diluted with nine times its volume of acidulated water. The platinum plates were cleaned according to the process pointed out by Faraday, which consists in making them red-hot, and rubbing them with a piece of potash whilst they are incandescent, and then plunging them into boiling sulphuric acid, and afterwards washing them in distilled water, constantly renewed. The platinum wires were cleaned in like manner, and inserted in glass tubes closed by the spirit lamp (*fig.* 239.), so as to present only a very small surface of contact with the liquid. The plate was bent into a spiral, and placed under a graduated tube filled with acidulated water, and intended for collecting all the gas that is liberated. The wire was introduced into a similar tube plunged into the same liquid. The communications

Fig. 239.

* The various decompositions and combinations, that are brought about by platinum, especially in the state of sponge, and which have been attributed to catalytic force — those especially that have been observed by M. Kuhlmann — appear to me to be capable of being very easily explained, by admitting an oxidation of platinum immediately followed by its reduction. We cannot, in fact, obtain these various phenomena, except so long as oxygen is present under one form or another.

of the plates and wire with the respective poles of the pile were established by means of platinum wires covered with glass tubes, so as to have no points of contact with the liquid (*fig.* 240.).

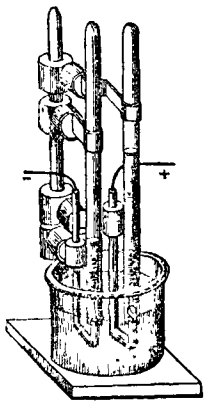

Fig. 240.

The following is the result of some of these experiments: —

Negative plate	- -	6 cub. in. of hydrogen.
Positive wire	- -	3 „ of oxygen.
Negative wire	- -	2·5 „ of hydrogen.
Positive plate	- -	·97 „ of oxygen.

There is wanting ·28 cub. in. of oxygen, which has been taken up by the plate. In the following experiment, the plate was placed immediately in communication with the positive pole, before having been with the negative: —

Negative wire	- -	1·22 cub. in. of hydrogen.
Positive plate	- -	·48 „ of oxygen.

·13 cub. in. of oxygen taken by the plate is wanting. The poles were changed: —

Negative plate	- -	·94 cub. in. of hydrogen.
Positive wire	- -	·61 „ of oxygen.

·28 cub. in. of hydrogen are wanting — namely, almost double—and, consequently, about the equivalent of the oxygen that had disappeared.

The following is another experiment, in which the plate, after having been thoroughly cleansed, was put into communication first with the positive pole: —

Negative wire	- -	1·22 cub. in. of hydrogen.
Positive plate	- -	·36 „ of oxygen.

·25 cub. in. of oxygen is wanting. On changing the poles: —

Negative plate	- -	·85 cub. in. of hydrogen.
Positive wire	- -	·61 „ of oxygen.

·37 cub. in. of hydrogen is wanting. There should have been a deficiency of ·48 cub. in., in order to represent the

equivalent of oxygen that has been taken up by the plate in the previous experiment. In general, it is rarely that we recover all the oxygen, that the plate has taken up, either because the liquid dissolves some of it, or because there is also a formation of oxygenated water, as we are about to see. The oxygen that is recovered, and that is equivalent to the missing hydrogen, is that which remains upon the surface of the platinum.

Spongy platinum, and a long platinum wire covered with the black powder, conduct themselves like the cleansed plate — namely, they absorb a large proportion of oxygen. In two successive experiments, the long platinum wire gave only 5 measures of oxygen against 20 of hydrogen, liberated on the short wire: 5 of oxygen were therefore wanting; 4 were recovered by changing the poles, for we had then no more than 12 hydrogen against 10 oxygen — a proof that 8 hydrogen had been absorbed.

Sometimes it would seem that a small portion of the oxide of platinum is dissolved, when the surface of the platinum, upon which it is formed is pulverulent, as when the acid is concentrated on boiling.

We have said that a portion of the gas is dissolved in the electrolytic liquid. But this solution is far from being the cause of the alterations in the proportions of gases liberated; indeed, when two platinum electrodes do not change functions, and always continue to be, one the positive electrode, and the other the negative, we find, after we have made allowance for the oxygen, that is absorbed by the former at the commencement, that the gases finish by being liberated in the proportions that constitute water, even when the electrolytic liquid is renewed around the surface of the two platinums. Moreover, the secondary polarities that are acquired by the platinum plates, and which they preserve entire, on being transported into another liquid, are a proof, that the gases have remained adhering to their surface — at least, the oxygen; for it might be that the property acquired by the negative plate is less due to the gas remaining adhering to its surface than to the state of purity, to which

it has been brought by the liberation of the hydrogen, that takes place upon it. We shall see this when, in the study of the sources of electricity, we are engaged with the currents produced by secondary polarities. With regard to the adherence of the oxygen, we have seen that it cannot be simply physical, as several physicists have admitted, but that it is rather a phenomenon of that superficial oxidation of which chemistry presents us with a great number of examples; since we are unable to explain the disaggregation of the metal, if a series of oxidations and reductions are not brought about. Moreover, we shall see further on, that in these cases the oxygen is in a peculiar state, which renders it more susceptible of attacking the platinum.*

The details, into which we have been entering, enable us now to explain the numerous anomalies that have presented themselves to several physicists, in the employment of voltameters with plates and wires of platinum. Faraday had already pointed out the errors that might be committed in making use of this instrument, and the precautions to be taken in order to avoid them. More recently Mr. Gassiott made several experiments with three voltameters,

* M. Schœnbein indeed has maintained that there has been no oxidation either of platinum or gold, but that there has been simply an adherence of oxygen to the surface of the metal. He supported his opinion on the facts, that the appearance of the metal does not change, that it does not lose a fraction of its weight at all in proportion to what it ought to lose, when the supposed layer of oxide is removed. Finally, he explains the disaggregation of the electrodes by a mechanical transport of particles analogous to that which takes place in the experiment with charcoal points. To these objections we may reply, first, that there is no transport of particles, since, on taking for electrodes a wire of gold and a wire of platinum, we never find the divided gold except upon the gold wire, and the divided platinum except upon the platinum wire; moreover, the conditions favourable to the production of the pulverulent layer are precisely the converse of those which physical disaggregation would require—namely, the absence of decomposition of the liquid, and a high electric tension. With regard to the appearance of the oxidised metal, it is true, especially in the case of platinum, that it differs but little from that of the pure metal; but it is the same with many other metals, when we are concerned with only a thin film of the sub-oxide, which, for the white metals especially, merely tarnishes their surface. Finally, it is well known by all chemists that their platinum crucibles end by being altered by the action of boiling nitric and sulphuric acids. We may even see, by leaving a morsel of spongy platinum for some days in a vessel filled with perfectly pure nitric acid, and hermetically sealed, that this acid acquires a colour which indicates the presence of nitrous acid, and consequently the oxidation of the platinum at the expense of the oxygen of the nitric acid.

whose electrodes were wires and plates of platinum of different dimensions, and which he filled either with distilled water, or with a solution of sulphuric acid. On placing them one after the other in the circuit, he remarked that the one with short wires always gave a proportion of gas a little higher than the other two. M. Poggendorff in order to collect the gases separately, and in order at the same time not to diminish too much the force of the current, by thrusting the glass tubes that collect them down into the electrolytic liquid, contrived a voltameter, in which the two graduated tubes that collect one the oxygen, the other, of double the section, the hydrogen, are prolonged below by a cylinder of porous clay; the two cylinders are fixed vertically at the bottom of a glass vessel filled with acidulated water, and the platinum electrodes are sealed to the bottom of the vessel so as to penetrate, one into one of the porous cylinders, the other into the other; and they come out exteriorly, in order to be placed in communication with the poles of the pile. In this manner, not only are the gases prevented from mixing, but the mixture of the liquids is also avoided, which, in contact with each of the electrodes, hold more or less in solution a portion of the hydrogen and especially of the oxygen; and there is thus no recomposition between these two gases.

This last precaution is the more necessary, as M. Jacobi has in fact remarked that the recomposition of the mixed gases takes place, even when the platinum electrodes do not come out of the liquid, as soon as there is above them a tube filled with the gaseous mixture, which is probably dissolved in proportion as that which is already beneath them disappears under the influence of the platinum, to re-form water. If the acids employed are very pure, and the electrodes perfectly clean, at the end of some hours, the combination is entirely brought about, and there remains no gas; the recomposition takes place still more rapidly when the surface of the platinum is pulverulent.

Temperature appears to diminish this facility of the gases liberated in the voltameters combining. This explains why M. Soret, on taking two voltameters perfectly similar, placed one

after the other for the same time in the same circuit, but one remaining cold and the other heated in a boiling vapour bath, constantly found that the heated one liberated a little greater proportion of gas. As soon as he allowed it to cool, the difference disappeared; the latter was constantly $2\frac{1}{2}$ per cent. In these experiments, the cold voltameter was kept in a mixture of ice and sea-salt. M. Soret determined the proportion of gaseous mixture, either by measuring it directly, or by dosing the hydrogen, as in an organic analysis; and by the two processes he arrived at the same result.

The difference, that we have just been pointing out, may be due to two causes; first, to the fact that oxygen, liberated at a low temperature, combines more easily with hydrogen, which causes the recomposition of the gases to be greater; then, to a formation of a bi-oxide of hydrogen, which does not take place at an elevated temperature. M. Meidinger has indeed observed, on employing for electrodes platinum plates 1·5 in. in length by 1·29 in. in width, and a solution of sulphuric acid of a density of 1·3, that the proportion of oxygen liberated is inferior to that of hydrogen at the ordinary temperature, and is slightly superior to it at an elevated temperature. This influence of temperature is the more marked, as the electric current is more intense. The hydrogen remains in general tolerably constant, as well when the acid solution is more or less diluted, as when its temperature is caused to vary; it is the quantity of oxygen that is generally less as the solution is more concentrated and colder. M. Meidinger had concluded from these various observations that, in the electrolysis of acidulated water, there is formed bi-oxide of hydrogen at the positive electrode. This conclusion is found to be confirmed by the fact that the acid solution acquires the property of decomposing iodide of potassium, a property possessed by oxygenated water; as well as by the faculty, possessed by the positive electrode, of liberating pure oxygen when, after having allowed the decomposition of the dilute acid to go on for a long time, this electrode is left in the liquid; but which it loses, as soon as it is transported into another liquid. Now, as we know that platinum, which has

served as a positive electrode for decomposing acidulated water, decomposes oxygenated water by its contact with it, this experiment is a proof of the presence of this compound in the liquid. We may moreover further prove it by heating the acidulated water; we then see an abundant liberation of oxygen arising from the decomposition of the oxygenated water, and this water loses by this the property of reacting upon iodide of potassium. M. Meidinger has remarked also that the oxygenated water, by diffusing itself in the electrolytic liquid, is able to react upon the hydrogen, liberated at the negative electrode, especially when this electrode has a large surface. Thus two identical voltameters having been filled, one with perfectly pure acidulated water, the other with electrolysed water, namely, charged with oxygenated water, only 14·27 cub. in. of hydrogen were found in the latter voltameter, whilst there were 14·64 in the former. It was merely necessary to introduce the platinum plate, which has been employed as a positive electrode, into the liquid in the tube, in which the hydrogen is liberated, in order to see the volume of gas gradually diminish, in consequence of the action exercised upon it, under the influence of the platinum, by the oxygenated water formed during electrolysis. We may add, that a low temperature and a small dimension of the positive electrode favour this formation of oxygenated water.

It follows, from the analysis that we have been making, and in particular from the labours of M. Meidinger, that, in order to obtain exact results with the voltameter, it is necessary to measure the hydrogen arising from electrolysis, and not the oxygen or the gaseous mixture; that we should employ, especially for liberating hydrogen, electrodes with small surfaces; that we must take this precaution of changing the acidulated water of the voltameter after each experiment, or at least of heating it so as to relieve it of all the oxygenated water, that it may contain.

Without detaining ourselves with other experiments of the same kind, we shall confine ourselves to relating, in addition, those by which M. Despretz, by operating on a large scale

with voltameters having platinum wires, and water either distilled or acidulated to various degrees with sulphuric acid, found that the quantity of gas liberated in each was, at least within a hundredth part, always the same, when they were placed in the same circuit for the same time. The voltameters that M. Despretz employed, had as electrodes platinum wires ·47 in. distant from each other; he had commenced by filling three of them with water, acidulated to $\frac{1}{10}$, $\frac{1}{20}$, and $\frac{1}{100}$ with sulphuric acid. In 8 minutes he obtained in each, with 12 Bunsen's pairs, 1·09 cubic inches of gas. On replacing the water that contained $\frac{1}{100}$ of sulphuric acid by distilled water, he obtained with 300 Bunsen's pairs ·903 cubic inches in each voltameter, except in that filled with distilled water, where there was a volume a little more considerable. The mean of four experiments, made with only two voltameters, filled the one with pure water, the other with acidulated water, gave him in 45 minutes ·6127 cubic inches in the pure water, and ·6156 cubic inches in the acidulated water. It is true that the temperature of the distilled water rises considerably, even to twenty times more than that of water, which contains only $\frac{1}{2000}$ of sulphuric acid. This explains why the gaseous volume in it is slightly more considerable, the gas not being able to dissolve so easily in it. Moreover the decomposition of distilled water presents other peculiarities; all the water (more than 61 cubic inches in M. Despretz's experiments) became frothy and whitish, which is due to the great dissemination of the gaseous molecules, whilst water acidulated to $\frac{1}{2000}$, as well as to $\frac{1}{10}$, remains perfectly transparent, and the liberation of the gas in it is only manifested at the extremity of the wires, under the form of a circle of bubbles; this remarkable difference, is due to the great resistance which the current encounters in its transmission through pure water, obliging it in this case to diffuse itself, and to pass by all the points of contact of the surface of the wire and of the liquid.

Whatever may be the case, we see therefore that in taking account of all these causes, which may disturb the manifestation of Faraday's law, and in endeavouring to avoid them,

this law is still found exact in the decomposition of pure water, as in that of acidulated water, and in the decomposition of saline solutions.*

We have seen that the chemical affinity of the substance, of which the electrodes are made, for one or other of the elements of the electrolyte, is able to facilitate its decomposition, and consequently the passage of the current. This property has been applied with great success by M. Becquerel to the production of various compounds, arising from the combination of the electrode with one of the elements liberated by the current,—compounds which he has succeeded in obtaining in the crystalline state, by employing only very small electric forces, that is to say, that of a single pair. He has in like manner obtained very remarkable

* M. Foucault thought he had found a proof of the existence of the physical conductibility of liquids, in the fact that of two voltameters with platinum plates, placed in the same circuit, and charged one with distilled water, the other with water acidulated with $\frac{1}{50}$ of sulphuric acid, the former, in the same time, gave only ·061 cub. in. of gas, and the latter ·61 cub. in. But this difference, in every case much too great, is due to the electrodes in each voltameter being formed of a bundle of platinum plates well arranged, maintained at perhaps $\frac{1}{100}$ in. from each other, and, by an arrangement of conductors, brought into electric states, alternately opposed. It followed from this arrangement, first, that the oxygen and hydrogen, being very near at the moment of their liberation, ought to recombine with each other, the more easily as they are disseminated over the entire surface of the electrodes, in distilled water, on account of its imperfect conductibility, as we have just seen in the case of M. Despretz's experiments. But, further, this same imperfect conductibility of water, joined to the very great approximation of the platinum plates, alternately positive and negative, caused the greater proportion of the two electricities to reunite between these plates under the form of the voltaic arc, and not electrolytically, as takes place through air and through liquid non-conducting bodies. We have in fact seen that M. Despretz, on operating so as to avoid these disturbing effects, has found that distilled water, like acidulated water, obeyed Faraday's law of equivalents.

To these indirect proofs in favour of the opinion that electrolytic liquids do not possess a physical conductibility analogous to that of solids, but that they can only propagate currents while being decomposed, a new and more direct proof has just been added; Mr. Faraday having proved the possibility of producing, by the action of an electro-magnet, an inductive current in a long column of acidulated water, contained in a tube of gutta percha, coiled as a helix around the electro-magnet. MM. Logeman and Van Breda have observed that the platinum plates or wires, by which this current is collected, are polarised; which proves that the acidulated water has been decomposed by the induced current. Now, if the propagation of the current can be brought about in an electrolytic liquid by way of physical conductibility, it must be in the case of a current induced in the liquid by an exterior current; and yet, even in this case, the propagation is accompanied by a decomposition.

secondary products by employing compound electrodes, and bringing about the combination of the elements, liberated by the current with one of the elements of this compound electrode. In a word, he has turned to account the chemical reactions that may arise from the liberation by the current of a body in the nascent state upon the surface of contact of a solid and a liquid.

It is not only by employing electrodes susceptible of entering into combination with the elements of the electrolytic liquid, or of being decomposed by them, that their decomposition may be facilitated. Grove, E. Becquerel, and Schœnbein have succeeded in obtaining the same result, still retaining electrodes of platinum, but dissolving in the liquid substances, which had affinity for one or other of its elements. Thus Grove has obtained, with the current of a single pair, the decomposition of water, by arranging the platinum positive electrode so that the portion that came out of the water was placed in a tube filled with hydrogen, which was itself in contact with the electrolysed acidulated water. The decomposition was facilitated by the affinity that hydrogen, under the influence of platinum, exercises over the oxygen of the water. E. Becquerel has succeeded, in like manner, in decomposing water by a feeble current, by dissolving in it either substances greedy of hydrogen, such as chlorine, bromine, and iodine, bi-chloride of copper, or salts whose bases are able to peroxidise, such as sulphate of peroxide of iron, which tends without ceasing to take oxygen from bodies that contain it. On placing in the same circuit a voltameter with ordinary acidulated water, and these various solutions, we obtain in the solutions proportions of oxygen and hydrogen variable with each of them, and even with the rapidity of decomposition, in consequence of the greater or less facility with which the oxygen or hydrogen combine with the substances dissolved. M. E. Becquerel found, on employing spongy platinum and gold for one of the electrodes, the other being a plate of platinum, that decomposition was facilitated, but that a great proportion of the gas was absorbed by that electrode which was made with the sponge. This is

always a consequence of divided platinum. M. Schœnbein had already employed spongy platinum as the positive electrode for combining the oxygen, arising from the water contained in alcohol, with this latter substance, and thus forming a more oxygenated product. He had in like manner succeeded in obtaining a more easy decomposition, by employing as negative electrodes sponges of platinum, that had been plunged into gaseous chlorine or bromine, and which thus exercised a powerful affinity over the hydrogen. The same effect is produced, and even in a higher degree, by taking as a negative electrode a plate of platinum, covered with a layer of peroxide of lead, the oxygen of which combines with the liberated hydrogen. All these facts, — and I omit many of the same kind — show to us the intimate relation that connects ordinary chemical affinity with the chemical force of the current, which, as Faraday judiciously remarks, is merely the same force transported to a distance, instead of being exercised only in contact. And indeed, we see, by all that precedes, how its action is facilitated, when it finds the concurrence of that of affinity. We shall complete the demonstration of the intimate connection, that exists between these two forces, when we shall be engaged with chemical action considered as a source of electricity.

There are, however, some cases that seem to form an exception to the general rule, that we have been laying down. It is that of certain metals which, when employed in a feeble degree of oxidation as positive electrodes, do not allow the current to pass; such is iron, when, as Schœnbein has observed, it is in the state called *passive*,— a state in which it is no longer attacked by acids, and is found modified in a very extraordinary manner, in its chemical properties, by the effect of the presence upon its surface of a film of a peculiar suboxide. Such again is copper, which, as Mr. Grove has observed, oxidises and gradually dissolves, when it serves as a positive electrode, in diluted sulphuric acid, to a current of moderate force, but which ceases to be dissolved, and stops the transmission of the current, when the latter becomes very strong, which is also due to the formation of a particular

oxide, which cannot combine with the acid. All these anomalies are rather phenomena purely chemical than electrochemical phenomena; for they are due to the impossibility of certain oxides combining with acids, in order to form salts, either because they contain too much oxygen, or because they contain too little.

Movements produced in electrolytic Liquids by the Passage of the Current.

The movements that are the effect of the passage of the current through electrolytic liquids, are of two kinds. Those of the first kind are the evident result of the decomposition of the liquid, and of the chemical reaction of the elements separated; those of the second are manifested by a transport through a porous diaphragm of a part of the liquid, and they seem to be rather a mechanical than an electrolytic effect. However, even in this case, it is not enough that the liquid be a conductor, as mercury would be; it must also be an electrolyte. We shall see to what extent this circumstance may throw light upon the phenomenon.

Davy was the first to observe that globules of mercury, placed between the two poles of a pile at the bottom of a vessel, filled with a solution which the current decomposes, elongate on the side of the negative pole, manifesting a peculiar trembling. Herschell made a detailed study of this kind of action, with which Serullas had previously been occupied, connecting it with the movements, that arise from certain chemical phenomena. Finally, Nobili has more recently, by new researches, completed the labours of Herschell, and found the true signification of this order of facts.

Herschell had placed at the bottom of a vessel very pure mercury, covered with a layer of concentrated sulphuric acid about ·4 in. in thickness; and he transmitted through this acid a current of a feebly charged pile. Immediately the current circulates, the acid is seen to undergo a rapid rotatory motion, due to a mechanical current that is established

between the two electrodes and which traverse directly the mercury; the particles of the acid, contiguous to the mercury, are those which move with the greatest rapidity. It is in the mercury that the cause of the movement resides; and we have the proof of this in the fact that we have merely to moisten with sulphuric acid the surface of the mercury and the vessel in which it is contained, in order to obtain a very rapid rotatory motion of this metal, employing this same film of acid for establishing the current. We should add that, when the globule of mercury is of considerable thickness, it experiences a continual tendency to elongate or to radiate toward the negative pole; and when it is very near to it, it reaches it and amalgamates with it. If it is small, its whole mass is set in motion with a very great rapidity, as if it were attracted by the negative wire. This apparent attraction is frequently very energetic, the globule moving with a great vivacity toward the negative wire, to which it adheres as soon as it comes into contact with it. The same effects may be obtained by substituting for sulphuric acid other electrolytic liquids, such as acids more or less concentrated, saline solutions of various kinds; but the intensity of the movement varies with the nature of the liquid. The mercury must in all cases be very pure; and there are generally observed currents, more or less violent, which radiate from the point nearest to the negative pole. With certain liquids, and especially the nitrates, there is also formed a current radiating from the positive pole, which, in some cases, even surpasses the other. These two currents coexist in the mercury, and in consequence of their action, there is formed in the globule of mercury a zone of equilibrium nearer to one pole than to the other, according as the current is more or less violent. On operating by means of an energetic pile, and with a great quantity of mercury, placed below very diluted solutions, we perceive in almost all cases these counter-currents, which come from the positive pole, especially if care is taken to keep this pole near and the negative pole far from the globule of mercury.

The experiments may be varied, by placing one of the

poles immediately in contact with the mercury, whilst the other is alone plunged into the electrolytic liquid. Very sensible currents are obtained, which radiate from the pole placed in this latter liquid: when it is the positive pole that is in contact with the mercury, these currents are less sensible on account of the promptitude with which the surface of the metal oxidises; but, by the agitations of the mercury, we detect the existence of currents beneath the film of oxide: moreover, on preventing the oxidation by a few drops of weak nitric acid, we see the currents established in this case as well as in the other.

The influence of this formation of an oxidised film over the movements, seems at once to show that these effects are not the simple result of a mechanical action, but that an electro-chemical phenomenon also takes place in them. This consequence, confirmed by other experiments of Herschell himself, to which we shall return, was completely confirmed by the analysis that Nobili made of these phenomena, connecting them with the formation of electro-chemical appearances. The learned Italian confines himself to substituting, in the apparatus that we have described *, for the metal plate a surface A B (*fig.* 241.), of very pure mercury, two or three

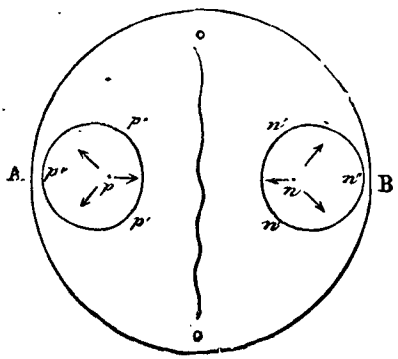

Fig. 241.

inches in diameter, which he covered with a solution of sulphate of soda, forming a layer about a quarter of an inch

* Vol. II. p. 399.

in thickness, into which are plunged two platinum points, in communication with the pole of a pile of moderate force, so as merely to leave between them and the surface of the mercury as small an interval as possible. The formation of two systems of currents is immediately perceived, terminated by limits that correspond with the shape of the ordinary electro-chemical appearances. These limits consist of two lines n', n', n'', and p', p', p'', on oval bands, within which the mercury is a little more depressed than it is without: the former is formed above the negative point, and the latter above the positive. In the middle, at o, o, the mercury presents one or two lines, where its surface appears to be agitated as by the conflict of two opposite currents, — a circumstance which, joined to those that we have already mentioned, clearly proves that the seat of the movement is at the surface of the mercury, and that the electrolytic solution merely follows the movement, impressed upon the particles of this metal. There is almost always formed at p a little oxide, which is carried by the currents outside toward the border, where it more or less accumulates; then it expands toward the negative side, which absorbs and reduces it, when the currents on this side are weakened to the point of no longer preventing its expansion. The negative currents disappear at the same time as the oval n, n,' n', as soon as the film of oxide is thrust by the positive currents beyond their ordinary limits. We have merely to oppose an obstacle to the expansion of this film, by means of a small plate of glass thrust in at o, o, to the surface of the mercury, in order to see the currents maintain themselves at n, and the film of oxide increase at p, so as to acquire sufficient consistence to destroy the positive currents; but, if the plate is removed before the oxidation is well advanced, the pellicle of oxide is seen to break into several fragments, the innermost of which expand toward the negative side, where they are absorbed and reduced, which weakens the negative currents, and at the same time revives the positive.

When other solutions are substituted for the solution of sulphate of soda, we obtain, according to the nature of the

solutions, either the two systems of radiating currents, or simply a single one; sometimes one, at other times the other. The cause of these differences is due to the circumstance that the elements which become deposited upon the secondary poles, formed by the mercury, cover its surface with a thin film, or leave it clear of all apparent deposit. Thus, there are no negative currents with solutions of salts with a base of copper, silver, tin, or bismuth, because the bases are reduced upon the mercury, and present to the eye films more or less consistent; whilst these same currents are very active with solutions of alkaline or earthy salts, the metals of which, in depositing, leave the mercury equally liquid and brilliant. The positive currents are in like manner wanting, whenever oxygen and acids are deposited in thin films upon the surface of the mercury; whence it follows that the currents may be said to be formed, only where the films, that bring about the electro-chemical appearances, are wanting.

The superposed liquids only follow the movement impressed upon the molecules of mercury. It is necessary, therefore, in order to appreciate the rapidity of their displacement, to take account of the degree of mobility that they possess upon the surface of this metal; but we must not forget that the vivacity of the movements of the mercury itself is due to the nature of these liquids, since it is an effect of their decomposition. Sulphuric acid, the drops of which, as we know, extend over mercury with an extraordinary rapidity, is of all the one that possesses the property in question in the most eminent degree. The most feeble electric force, such as that resulting from a pair formed by the mercury itself, the sulphuric acid, and an iron wire plunged into it, is sufficient to bring about the phenomenon.*

* The following is the process adopted by M. Nobili. He plunges a drop of mercury into a bath of sulphuric acid, and touches it towards its edge with the extremity of an iron wire; the drop immediately contracts and ceases to touch the iron; then, resuming its natural form, it comes anew to meet the iron point, to contract and again to expand; thus continuing an alternate motion of contraction and dilatation so long as the voltaic action of the three elements of the pair continues, namely, mercury, iron, acid. This result is only effectively obtained by employing iron or other easily oxidisable metals: the contact of gold or of platinum does not produce any effect.

The experiment may be made under a very remarkable form, and which requires only a very feeble pile. We take a mass of mercury, to which we endeavour to give a very circular form of about an inch in diameter, and cover it with a very limpid alkaline solution. A platinum point, communicating with the negative pole of the pile, is placed above the centre of the drop of mercury so as to touch its surface slightly; a second similar point, to which the positive pole is connected, is plunged into the solution over the figure of the mercury, at a distance of nearly half an inch from its outer edge. As soon as the circuit is established the mercury flattens notably, and appears under the form of a star, with four blunt points, one of which reaches and touches the positive wire; immediately this contact takes place the mercury returns upon itself, rising toward the negative point, which it touches afresh, then it flattens, and so on in succession. In its return movement, the circular drop again presents itself under the aspect of a star, the obtuse points of which are found where the intermediate spaces of the former were.

The effects, that we have been describing, already tolerably complex, become still more so, when the mercury is alloyed with a very oxidisable metal. Sodium, in particular, by its amalgamation with mercury, brings about still more decided movements than other metals of the same kind, although all those that are oxidisable possess more or less the same property. Herschell and Nobili have successively studied with care this influence of metals, which had moreover been already pointed out by Ermann, Pfaff, and Serullas; this latter chemist had observed it directly, without the assistance of the pile. He had endeavoured to analyse the singular gyratory motions acquired by the alloys of potassium with different metals, when they float in small fragments upon mercury under water; those produced by the alloys of potassium and bismuth had appeared to him particularly energetic and durable.

It is evident that, in the experiments of Herschell and Nobili, which we are about briefly to relate, the effects due to the presence of sodium or of similar metals, derived from

electrolysis, are only secondary, since they may be obtained by alloying the mercury directly with these metals; but as they combine with the more direct effects of the current, they must be analysed, in order that we may give a good account of these latter.

The most simple manner of manifesting this order of phenomena consists in plunging in mercury (*fig.* 242.), when

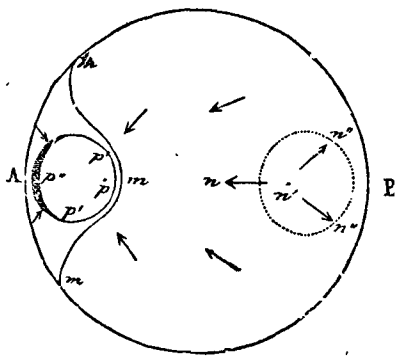

Fig. 242.

it is covered with sulphate of soda, the negative point, so as to have at $n\ n'\ n''$ a single negative point above the positive point. This simple immersion revives the negative currents, due essentially to the liberation of sodium, which unites with the mercury; a contact of a minute is sufficient to charge the amalgam with as much sodium as is necessary for producing the following effects. At the moment when the negative point is withdrawn from the mercury, the positive currents are seen to disappear around the point p; on the contrary, a system of currents is observed which converges rapidly, from all points of the circumference of the mercury, towards the centre. These currents have different velocities which inflect the spot at A; the latter has in front of it a line or band $m\ m\ m$ more or less vivid, which advances towards the point n in proportion as the motion diminishes, and ends by forming the dotted oval around this latter point, when, the sodium being all oxidised, the phenomenon returns to its primitive state.

The essential point, that was remarked by Herschell and confirmed by Nobili, is the inversion of the motion at the spot of the positive currents, produced by the presence of the sodium in the mercury. M. Nobili attributed it to the circumstance that the sodium, which has a powerful tendency to unite with the oxygen and acids, that are found in a nascent state at *p p'* and *p''*, travels rapidly thither, and thus brings about a very rapid system of current, directly opposed to the radiation, that takes place when the mercury, being deprived of this eminently oxidisable metal, has nothing else to do than to propagate from the centre to the circumference the impulse, which it receives from the oxygen and the acids liberated.

Whilst a part of the sodium arrives from all sides to be converted into alkali, under the influence of the oxygen, the mercury itself receives at *n n* and *n''* another part of the sodium, which produces the ordinary negative currents; but, on account of the movements brought about by the sodium already present, the ordinary shape of the negative appearance is deformed and elongated to the extent of being transported from the interior side to *m m m*, which at the same time causes the other depression *p p' p''* to incline notably towards A. The latter rises and re-forms itself around its centre in proportion as the motion is weakened by the loss of sodium, that is suffered by the amalgam. When the oval reappears around the point *n*, it is a sign that the oxygen of the positive spot has no longer any sodium to oxidise; it then attacks the mercury and covers it again with a film, which soon prevents all movement.

We shall not insist upon the effects, that are obtained by plunging into amalgams, covered with an electrolytic solution, a wire of copper or of platinum, because these are effects of the same kind as the preceding, seeing that thus a voltaic pair is produced; nor shall we dwell upon the numerous experiments of Herschell, made with various amalgams and different solutions, because they are the same phenomena, and with nearly the same intensity. We shall confine ourselves to two remarks. The first consists in pointing out this curious property of a very oxidisable metal, amalgamated with mer-

cury, of travelling, under the influence of this current, to the place, where it finds oxygen and an acid, with which it can combine. We shall return to this when occupied with the electricity, liberated in voltaic pairs, of which one of the elements is an amalgam. The second remark is, that the movement of the mercury in the ordinary case is evidently due to the absorption, that it exercises over the elements, that are deposited upon its surface by electrolysis; not only over oxygen on the one hand, and over sodium and other metallic bases on the other hand, but also over hydrogen, of which we shall see proofs further on. And indeed, as soon as these elements cease to be absorbed, but remain upon the surface, the movement ceases. With regard to the movements themselves, they are not a mechanical effect of the current, analogous to the electro-dynamic phenomena of repulsion and attraction; for the strongest magnets do not modify them, whilst, as we know, they bring about energetic rotations upon mercury, which simply transmits currents, without the intervention of any electrolytic liquid. These movements, therefore, are the results of purely chemical actions; they are analogous to those which are produced in a host of combinations, in which the bodies are mobile, either on account of their being liquids, or, although solids, on account of their floating upon a liquid, as sodium and potassium, or being able to glide along a smooth plane, as globules of tin or iron in ignition. The effect of the current in the phenomena, that have been engaging our attention, is simply to impress a direction upon these movements, because it impresses one upon the chemical action, by transporting by electrolysis, into determinate points, the elements among which it is exercised.

The movements of mercury, again, may be produced in a remarkable manner, by means of a succession of instantaneous currents, determined alternately in contrary directions, such as those obtained by induction with Saxton's machine. One of the ends of the induced wire is put into communication with mercury placed in a cylindrical capsule, and the other, with a platinum point, plunged in an electrolytic solution, such as sulphuric acid, diluted with nine times its

volume of water, which covers the surface of the mercury, so as to be $\frac{1}{6}$ or $\frac{1}{8}$ of an inch distant from it, and to correspond with its centre. As soon as the currents pass, the mercury is seen to be agitated, and to assume a vibratory motion with undulations, setting out from the centre, and the circular, elliptical, or polygonal form of which depends upon the shape of the vessel.

A very curious effect also is obtained, by placing mercury in a tube, bent into the form of an inverted syphon, and making one of the vertical columns communicate with the negative pole of a pile, whilst the positive is plunged in an electrolytic solution, which covers the summit of the other; a depression is produced in this latter column and consequently a difference of level, between the two columns of mercury, which is greater or less according to the intensity of the current.* It would seem that there is in this case a phenomenon analogous to what is presented by the voltaic arc, when mercury is taken for the negative electrode; however, as the effect is able to be produced by a very feeble current, it is probable that it is, like the preceding, purely electro-chemical.

I will not dwell further upon the class of effects, that I have just described, and to which a greater degree of importance had generally been assigned, than they really merit. They may at the most be considered as connected with the part played by mercury in electro-chemical phenomena; a

* Gerboin, in 1801, was the first to point out these movements. He operated with a tube bent in a U form, or an inverted siphon; the tube was filled with mercury to half the height of its vertical branches; the surface of the mercury at the summit of each column was covered with a stratum of water, into which were plunged two wires, that communicated respectively with the poles of the pile. It is especially on the surface of that column of mercury which, being beneath the positive pole received the hydrogen arising from the decomposition of the water, that he perceived movements, which were manifested by the tendency of small light bodies thrown into it, to move from within outwards upon the surface of the tube. But, if the positive point were made to touch the mercury, the movement of the small light bodies immediately took place in the contrary direction, namely, from the circumference to the centre; the mercury appeared also to be depressed beneath the positive point, when this point was very near to it.

No effect took place upon the surface of the mercury, placed beneath the negative point; it was merely oxidised.

very singular part, it is true, in cases of amalgamation, and to which, as I have said, we shall have occasion to return, but which is, nevertheless, of very limited interest, in consequence of its special character.

The second species of movement, that we have pointed out at the commencement of this paragraph, consists of a transport, that is brought about through a porous diaphragm of a liquid traversed by the current. Porret, who was the first to observe it, made the experiment by separating a cup into two compartments, by means of a diaphragm of bladder, and placing common water in each, with the positive pole of a pile in one of the two, and the negative in the other. At the end of a short time, the water is seen to pass through the bladder, the resistance of which it surmounts, from the positive compartment into the negative, where it retains itself at a more elevated level. The phenomenon is very decided, only so long as the liquid is an imperfect conductor, like unto pure water; with acidulated water it no longer takes place. M. Becquerel has obtained a phenomenon of the same kind with two tubes half-filled with clay and with water; the lower mouths of which, being closed by plugs pierced with small holes, were plunged into water, whilst the interior liquids of each tube were placed respectively in communication with each of the poles of a pile, by means of platinum plates. The clay was driven from the tube, into which the positive pole was thrust and not from the other.

It follows, from these experiments, that there is a very decided tendency of a liquid, traversed by a current, to travel from the positive pole towards the negative, provided it presents a certain resistance to the passage of the current. M. Wiedemann succeeded, after very accurate researches, in discovering the laws of this phenomenon. In a first series of observations, his object was to determine the relation of the intensity of the voltaic current to the quantity of liquid, transported in a given time. The liquid was contained in a large glass vessel *h h* (*fig.* 243.), and in a cylinder of porous clay, *a*, occupying the middle of the great vessel. Upon the cylinder of clay was cemented a bell-glass *c*, the neck of which allowed of the passage of a vertical tube

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d, furnished with a lateral escape-tube *e e*. At the interior and the exterior of the clay cylinder were placed two platinum plates *g* and *i*, coiled into a cylinder, each of them communicating with vertical wires *f* and *k*, that might be placed in communication with the poles of the pile. The small opening, through which the wire *f* traversed the bell-glass *c*, was hermetically closed with mastic; the adaptation of the vertical tube *d* to the neck was sufficiently perfect to render the escape of the liquid impossible. The cylinder of porous clay had been immersed for a long time in diluted hydrochloric acid, before being used for the experiment; it was thus freed from all soluble matters, that it might contain.

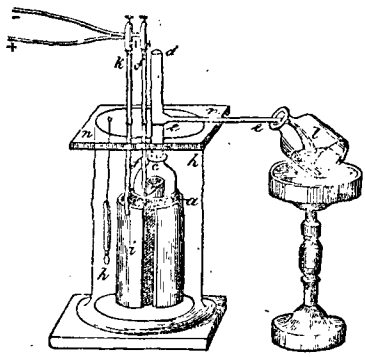

Fig. 243.

As soon as the current was established in the direction indicated in the figure, the liquid rose in the tube *d*, and was not long before it passed out by the lateral tube *e*, when the level had in a slight degree surpassed the orifice of this tube; the flask *l* was for receiving the liquid that ran over. The phenomenon was the result principally of an action proper to the current, but there were also some secondary causes, the influence of which it was essential to estimate and to eliminate.

One might at first have feared that the pressure, resulting from the elevation of the level in the tube *d*, might tend to counteract the phenomenon, and to diminish the quantity of liquid transported through the porous cylinder; but a direct experiment showed that there was no foundation for this fear. The apparatus was filled with water, so as to establish in the tube *d* an elevation of level, equal to the elevation observed; and the experiment was left to itself for several hours, without making any current pass. The level having

remained invariable, it was concluded that the pressure exercised was not sufficiently powerful to cause any appreciable quantity of water to pass through the diaphragm.

At the commencement of the experiment, the elevation and the escape of the liquid were due in part to the bubbles of hydrogen liberated upon the negative plate, which came and lodged themselves in the various parts of the apparatus; but, at the end of a few moments, the accumulation of gas attained its maximum, and the new bubbles formed were liberated incessantly by the tube *d*. Then alone were the observations commenced. Evidently nothing similar took place when metallic solutions were experimented upon.

Finally, if the experiment continued for a long time, the intensity of the current remaining constant, the quantity of liquid, escaped in a given time, underwent a little increase. At the same time, the liquid, placed within the interior of the porous cylinder, was disturbed by the presence of very fine particles of the material of the cylinder. These particles were evidently torn off by the liquid from the pores of the diaphragm; these pores must therefore have become larger, and hence arose the increase, that was observed of the liquid current.

The current was produced by a Daniell's pile, and measured by a tangent-compass, or by a galvanometer, compared directly with the compass.

The two following tables demonstrate, in an evident manner, that *the quantities of liquid, transported in equal times, are proportional to the intensities of the currents.*

I. Distilled Water.

Quantity q of Liquid transported.	Intensity i of the Current.	Relation $\frac{q}{i}$.
grs.		
17·77	14·4	1·23
13·26	10·8	1·23
10·59	8·3	1·27
7·46	6·0	1·24
5·89	4·8	1·23
4·47	3·6	1·24
3·38	2·9	1·17
		Mean 1·23

II. SULPHATE OF COPPER.

q.	i.	$\frac{q}{i}$
grs.		
2·48	10·6	0·234
2·32	10·1	0·230
2·26	9 8	0·231
2·11	9·3	0·226
1·49	6·5	0·229
1·25	5·35	0·233
		Mean 0·230

M. Wiedemann has also found, on covering successively various portions of the surface of the cylinder with a coating impermiable to the liquid, and a non-conductor of electricity, then by gradually diminishing its thickness, that *the quantities of liquid, transported by a galvanic current, through a porous partition, are independent of the extent of this partition and of its thickness.* He found no law, by which the quantity transported is connected with the resistance of the liquid; but he has remarked, as I had observed in 1825, that very good conducting liquids, such as diluted sulphuric acid, are not transported in any appreciable proportion.

The experiments, that have just been described, were subject to a very grave objection; in fact, they only measured a complex phenomenon, produced by the combination of two causes, altogether different, namely,—the action proper of the current, and the friction of the liquid in the pores of the diaphragm. This latter cause evidently allowed of no comparability being established between the experiments relative to different liquids. On this account, M. Wiedemann has sought for a mode of experimenting, which was independent of this disturbing action; and he caught the idea of measuring the hydrostatic pressure, that could cause the phenomenon of transport to disappear; and which consequently would form an equilibrium with the action proper

of the current. The apparatus previously described was consequently modified. The capillary tube *e*, was placed in communication with a small mercury manometer *e*, *p*, *m* (*fig.* 244.), and the upper extremity of the vertical tube *e* (*fig.* 243.), was hermetically sealed after the introduction of the liquid. Under these conditions, the passage of the current, instead of producing a constant escape of the liquid, brought about a displacement of the mercury in the manometer; and this displacement was stopped, when the pressure, due to the difference of level of the manometer in the two branches, was sufficiently powerful to cause a quantity of liquid, equal to that, which the voltaic current would draw along, to repass at each instant through the pores of the cylinder. It is evident that it was necessary to avoid, in this arrangement of the apparatus, all liberation of gas in the tube *d*; and, consequently, that we ought to confine our experimenting to solutions of metallic salts. Pure water, or water simply acidulated, or solutions of alkaline salts, are not admissible in this kind of experiment.

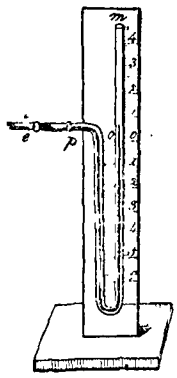

Fig. 244.

Numerous experiments upon solutions, variously concentrated, of sulphate of copper, led to the following law: —

The heights to which the mercury rises, in the manometer, are proportional to the intensity of the current, in inverse ratio to the surface, and in direct ratio to the thickness of the porous diaphragm.

These results agree perfectly well with those of experiments upon the quantities of liquid transported, if we take into account the laws of the escape of liquids, by capillary tubes, as they have been determined by MM. Hagen and Poisseuille. We know, in fact, that the quantities of liquid, which escape in equal times by very narrow capillary tubes, are proportional to the pressure and in inverse ratio to the length of the tubes. Now, a porous diaphragm may be compared to a system of capillary tubes, the number of which is evidently proportional to the superficial extent of the diaphragm, and the length proportional to the thickness. The quantities

of liquid, transported by the voltaic current, being proportional to the intensity of this current and independent of the thickness of the diaphragm, the pressures capable of producing in an inverse direction the transport of an equal quantity of liquid, must be proportional to the intensity of the current, and to the thickness of the diaphragm. The influence of the superficial extent of the diaphragm is no less evident; the pressure, that brings about the passage of a given quantity of liquid through a system of equal capillary tubes, must be in inverse ratio to the numbers of these tubes.

Finally, the influence of the nature of the liquid is manifested in a very simple manner in this second class of experiments. *The height of the mercury in the manometer is proportional to the electric resistance of the liquid.* At least we may conclude this from a series of observations, relative to solutions of sulphate of copper, into which the current was introduced by copper electrodes, so as to avoid all polarisation. These observations are summed up in the following Table: —

Proportion of crystallised Sulphate for 100 parts of the Solution.	Electric Resistance of the Solution.	Relation of the height of the Mercury to the Intensity of the Current.	Quotients of the Numbers of the 3rd Col. by those of the 2nd.
16·25	18 0	1·35	0·0750
9·22	27·0	1·98	0·0733
6·6	32·5	2·44	0·0750
3·4	55·5	3 79	0·0683
1·3	100·0	6·80	0·0680
			Mean 0·0719

The constant approximation of the number of the fourth column is a satisfactory proof of the accuracy of the law. In summing up all these laws we may say, that *the force, with which a voltaic current tends to transport a liquid through a porous partition from the positive towards the negative pole, is measured by a pressure, which is directly proportional to the intensity of the current, to the electric resistance of the liquid, and*

to the thickness of the partition, and inversely proportional to the surface of the partition.

M. Wiedemann remarks, that the simple laws, to which he has found the mechanical actions of the current to be subjected, are the same as those that have been assigned by Ohm for the distribution of electricity in a closed circuit. But, the question that presents itself here is to know whether these mechanical actions are indeed the direct effect of the current, or whether they are not an indirect consequence of an electrolytic phenomenon. This latter opinion, which had already been put forward by M. Raoult, at the end of experiments, more or less doubtful, was taken up by Mr. Graham, who considers that, like as in the decomposition of acidulated water, one equivalent of sulphuric acid goes with the oxygen to the positive electrode, whilst one equivalent of hydrogen is liberated at the negative; so, in the decomposition of pure water, a basic radical composed of several atoms of water, and of one equivalent of hydrogen, goes to the negative electrode, whilst the equivalent of oxygen is liberated at the positive. This manner of viewing the phenomenon would suppose that water, when under the influence of an electric current, by which it is polarised, would assume a peculiar chemical constitution, in virtue of which a considerable, but yet variable number of atoms of water, would be associated together to constitute one molecule of liquid water, of which one atom of oxygen would form the negative or acid radical, analogous to chlorine, remaining apart; whilst all the other atoms would form a basic or positive radical, containing definitively one equivalent of hydrogen, which is not neutralised, and which gives to it basic affinity, as takes place in many organic radicals. Now, it is this voluminous basic radical, which is transported in the electric decomposition of pure water, and is decomposed into gaseous hydrogen and into water at the negative electrode, producing that accumulation of water which is observed; at the same time oxygen is liberated alone at the positive electrode. The porous diaphragm is necessary for giving evidence of this accumulation of water at the negative electrode, in order to prevent the liquid regaining its

level, as was necessary in Daniell's experiments, to give evidence of the accumulation of acid at the positive electrode, in the decomposition of acidulated water. The analogy is still more complete when a voltameter, with acidulated water, is placed in the same circuit in which the partitioned apparatus is situated, full of ordinary water. I satisfied myself that the quantity of gas liberated in this latter apparatus is exactly equal to that, which is liberated in the voltameter. Now, if there were in the fact of the transport of the water a mechanical labour, independent of electrolysis, it ought to find its equivalent in a more abundant decomposition of water in the voltameter; which does not take place, whence it would seem to follow, that in the two apparatus there are simply two equivalent chemical effects; one, the decomposition of acidulated water with oxygen and acid at the positive electrode, and hydrogen at the negative; and the other, the decomposition of pure water with oxygen at the positive electrode and of water and basic hydrogen at the negative.

The hypothetic constitution, that water would assume under the influence of electric polarity, would present nothing astonishing; for, like as a molecule of oxygen, or of any other simple body, is composed of a group of chemical atoms more or less numerous, nothing prevents our supposing that a molecule of water is composed of a group of chemical atoms of water (each composed of 1 chemical atom of oxygen, and 2 of hydrogen) more or less numerous. In this group one atom of oxygen is detached by the passage of the current, whilst the other atoms of the water, with the two atoms of hydrogen, form a similar group with the atom of oxygen of the group or of the following molecule, according to the theory of Grotthus, as far as the negative electrode, where they finally become free.

Mr. Graham, applying the same ideas to ordinary endosmose, sees, in this class of phenomena, an effect of electricity produced by chemical action, that the liquids between which the porous substance is interposed, exercise upon this substance itself; he gives the name of *osmotic* force to this particular form, which electric force so produced assumes;

he thus explains why the phenomenon is much more frequent and more decided with animal membranes, than with porous earths. It is not the same when, the endosmose being electric, the electricity is furnished to the liquids directly by an exterior source; a case, in which the nature of this porous diaphragm has no other influence than that resulting from the greater or less facility, with which it allows the electric current to pass. We shall return to this subject when we shall be treating of the electricity developed by chemical actions, the endosmose of which would in this theory be simply a remarkable manifestation; we shall then examine to what point Mr. Graham's ideas may be reconciled with the laws found by M. Wiedemann and with the facts, which seem to prove that endosmose may take place, without any apparent chemical action.

We shall not terminate this paragraph without referring to Mr. Napier's experiments on electric endosmose, which, although they are not contrary to the manner in which Prof. Graham views this phenomenon, nevertheless demonstrate the necessity there is of studying it still more closely, than has been done by the celebrated English chemist. One of the most remarkable consists, in placing the two electrodes of a pile, each in a porous vessel, filled, the one, in which the positive electrode is plunged, with hydrochloric acid, and the one, in which the negative electrode is plunged, with pure water; the two porous vessels being themselves plunged in pure water. When the current has passed for several hours, a little hydrochloric acid is found in the intermediate water, but not a trace in the negative vessel; in which, on the contrary, the quantity of liquid has sensibly augmented at the expense of the exterior water. On changing the places of the electrodes, the distilled water is seen to pass from the positive cell into the intermediate vessel, and the acid, which communicates with the negative electrode, experiences no change; endosmose, as in the preceding case, only taking place between the vessels filled with pure water. There is indeed a chemical decomposition, but it is very feeble. It is not necessary, in order to produce electric

endosmose, that the current should be very strong, provided that it be sufficiently prolonged. Mr. Napier has succeeded, with the current of a single pair, the zinc and copper of which were plunged into two compartments, separated by a porous diaphragm, and each filled with distilled water, in making a volume of water of about 2lbs. weight pass from the positive compartment to the negative at the end of forty days; the current indicated only 3° on a very sensitive galvanometer, placed in the circuit; and with regard to the decomposition of the water, it was evident, since at the end of the forty days the zinc had lost 38½ grs., which represents the quantity oxidised during the course of the experiment.

Chemical Effects of ordinary Electricity, and of the Electric Spark.

A long time before the discovery of the decomposition of water by the voltaic pile, physicists had succeeded in producing chemical effects, by the electricity of electrical machines. I do not speak of the effects of oxidation, that accompany the incandescence of metals, by electric discharges, observed by Van Marum and by others; because electricity, in this case, contributes to it only indirectly, by heating the wires. But, in 1790, Paetz and Van Troostwik had decomposed water into its constituent gases, by causing the electric spark to arrive, by means of a very fine gold wire, into the interior of a glass tube, filled with water, and causing it to come out, by means of a second similar wire, also immersed in the water, at some distance from the former, and communicating with the ground. It requires a very powerful discharge to bring about the decomposition, and the employment of a Leyden jar is necessary; but, in order not to have a discharge that breaks the tube, the two gold wires are placed apart, so that their ends shall be about an inch and a half distant from each other; little sparks are then made to pass between them, the force of which is gradually increased, by approximating, little by little, a conductor, which communicates with one of the wires, towards the outer coating of the Leyden jar, until very small bubbles of gas are seen to rise

in the water of the tube. As soon as the necessary power of electricity has been discovered, the two gold wires are brought near to each other, so as to obtain in the dark a small glow of about $\frac{1}{25}$ of an inch at their extremities, immersed in the water. This distance is the most favourable; for, if the wires are brought nearer together, the spark passes from one wire to the other through the water, and breaks the tube. The passage of 500 sparks produces a considerable quantity of gas, which inflames, leaving only a small residue, by the passage of the spark. This residue arises from the air, that had remained dissolved in the water; it is no longer presented when the experiment has been made four or five times successively with the same water.

Cuthbertson and Pearson also succeeded, by means of a very great number of discharges, in extracting from water a small quantity of the mixed gases, oxygen and hydrogen. But the philosopher, who obtained the most decided effects of chemical decomposition by means of ordinary electricity, was Wollaston, who, in 1801, a short time after the decomposition of water by the pile, showed that, without a Leyden jar, and without even powerful electrical machines, we may succeed in approaching as closely as possible to the conditions under which we operate with the voltaic pile. He devised the plan of introducing a gold wire into a capillary tube, giving to it as sharp a point as possible; then, after having heated the tube to the extent of causing it to adhere to the point and to cover the latter in all parts, he ground it down gradually, until he was able, with a lens, to discover the extremity of the gold wire.* On passing through the water electric sparks, drawn from the conductor of the machine, by wires thus enveloped, he succeeded in the decomposition, by means of sparks of $\frac{1}{10}$ of an inch in length, with a point, that was not more than a $\frac{1}{1000}$ of an inch in diameter.

If this diameter is still further diminished, a continuous liberation may be obtained of small gaseous bubbles, merely establishing complete contact between the wire and the con-

* The same process is equally applicable to platinum wires; we have employed it for obtaining electrodes that should present the smallest possible point of contact with the liquids (*fig.* 239.).

ductor of the machine, without producing any visible spark between them. Two currents of gas may be obtained in like manner, by causing the electricity to pass from the two sides of the water, at the same time, by means of fine points, of which one communicates with the positive conductor, and the other with the negative conductor of the machine. However, the phenomenon, notwithstanding the similarity of appearance, does not take place in the same manner as with the pile; for each wire liberates at the same time oxygen and hydrogen, instead of producing them separately.

Wollaston had, however, succeeded in decomposing salts, by ordinary electricity, as by the pile; thus, having plunged two silver wires, covered with wax, except at their very extremities, into a solution of sulphate of copper, and having made one of the wires communicate with the positive conductor and the other with the negative of an electrical machine, he obtained, at the end of a hundred revolutions of the machine, a deposit of metallic copper at the negative wire, whilst the positive wire presented nothing similar. In like manner, having passed a current of sparks between two very fine gold points placed at the distance of an inch from each other on a card coloured with a strong tincture of litmus, he remarked, after a very small number of turns of the machine, a very visible red spot, around the positive wire; on placing the negative wire near the same spot, it was soon seen to regain its colour.

Wollaston's experiments fairly demonstrate the decomposing power of the electricity of ordinary machines; but they still allow of certain doubts as to the nature of the mode of decomposition. Is it a simple decomposition? or is this decomposition accompanied by the transport of elements, which characterises the effect of the current and which we have named electrolysis?

M. Bonijol, it is true, had succeeded in decomposing water electrolytically, by means of atmospheric electricity, by employing an apparatus with fine points, with which he had also decomposed it by means of ordinary electricity. He drew off atmospheric electricity by the intervention of a point placed at the extremity of an insulating rod, and commu-

nicating, by a very fine wire, with the apparatus in which the decomposition is brought about. The same philosopher had also succeeded in decomposing solid potash and chloride of silver, by placing them in a very narrow tube, and causing them to be traversed by a series of electric sparks, brought into the tube, by means of two wires, one communicating with the conductor of the machine and the other with the ground; at the end of five or ten minutes there was found in the tube either potassium, which took fire, in proportion as it was reduced, or sodium. But, neither in this case, could it be proved whether the decomposition was electrolytic or not.

Faraday, after having confirmed the accuracy of those experiments of Wollaston's which are favourable to electrolytic decomposition, succeeded in demonstrating it in a much more evident manner. He took for this purpose a glass plate, upon which he applied two pieces of tin-foil *a* and *b* (*fig.* 245.), which he placed in communication, by means of

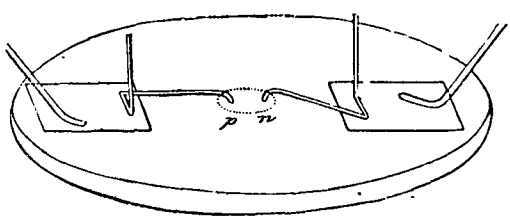

Fig. 245.

insulated wires *c* and *d*, one with the positive conductor of an electrical machine, and the other with the negative conductor, or with a discharging apparatus*; from each of these plates of tin was led a fine platinum wire, well in contact with them, and abutting, one at *p*, the other at *n*, forming thus a positive and a negative pole. A drop of sulphate of copper, having been placed upon the glass plate, so that the points *p* and *n* might plunge into it, there was precipitated, after twenty turns of the machine, so much copper at *n*, that the wire appeared to be entire copper; no spark passed.

* We have already pointed out in Vol. I. that Faraday means, by discharging apparatus, a system of conductors, such as the pipes employed in conveying gas for illumination, which communicate in a perfect manner with the ground.

Iodide of potassium, mixed with starch, very rapidly gave off free iodine at *p*.

The last mode of operating for experiments of this kind, is to moisten a piece of filtering paper with the solution, that is required to be decomposed, and to place it between the two points *p* and *n*. Thus the paper saturated with a solution of iodide of potassium in starch, is seen to become blue at *p*, after the machine has been turned scarcely half a turn; this is the most sensitive chemical test, that it is possible to find. A piece of litmus paper, saturated with sulphate of soda, immediately becomes red at *p*, whilst turmeric paper, moistened in like manner, becomes red at *n*, by the effect of the liberation of alkali. The effects of voltaic electricity may be still better imitated by arranging (*fig.* 246.), one after the

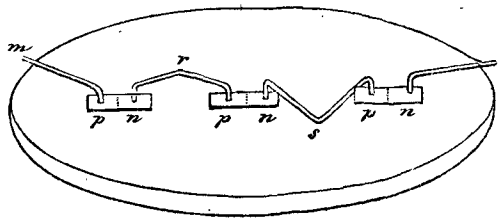

Fig. 246.

other, upon the glass plate, several small pieces of paper, half litmus and half turmeric, moistened with sulphate of soda, and connecting them by metal conductors of platinum, *r*, and *s*, so that the extremities *n*, of these wires, and of the extreme wire *t*, which communicates with the negative conductor, shall be in contact with the turmeric paper, and as the extremities *p*, of the same wire and of the extreme wire *m*, which communicates with the positive conductor, shall be in contact with the litmus paper, the points *r* and *s*, resting upon the glass. After several turns of the machine, we see, from the colour assumed by the paper, that acid is liberated at all the points *p*, and alkali at all the points *n*.

It is necessary, in all these experiments, to take care to avoid the passage of the spark over the moistened papers; because it is affected by the nitric acid, the formation of which

is brought about by the spark, by producing the combination of the nitrogen and oxygen of the air.

The same effects may be obtained by employing only a single conductor conveying one of the electricities to one of the ends of the moistened papers, and causing the other end to communicate with the ground, or simply with the air, by means of a linen or hempen thread of any desired length, moistened with the same solution as the paper, and suspended by silk threads, so as to be insulated. The point where the metallic extremity of the conductor terminates, manifests the liberation of acid or of alkali, according to the nature of the electricity that reaches it. A single metal pole is able, therefore, to produce decomposition, and to receive one of the elements, whilst the other is liberated somewhere at the opposite extremity of the liquid conductor; for example, against the air, which may itself serve as a pole or electrode. Faraday quotes several experiments, which proves the reality of this latter supposition. Thus, a piece of turmeric paper *a*, and a piece of litmus paper *b* (*fig.* 247.), having been

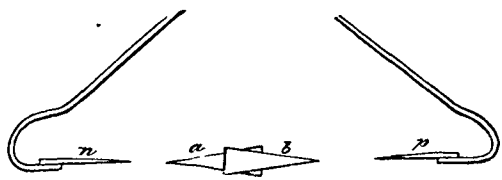

Fig. 247.

moistened in a solution of sulphate of soda, were placed on wax between two needles *p* and *n*, which were in communication, one with the conductor of the machine, by means of a wire, and the other with the discharging apparatus; the interval between each point and the extremity of the corresponding paper band was about $\frac{1}{2}$ an inch; the point *p* was opposite to the litmus paper, and the point *n* to the turmeric paper. As soon as the machine was touched, decomposition took place; the extremity *b* manifested the acid reaction, and the extremity *a* the alkaline re-action; which indicates that the positive electricity arrives from the point *p*, through the air to *b*, where it penetrates into the moistened

paper, and the negative, in like manner, from the point n to a. In this case the air, on both sides equally, fills the office of electrode; a result, which can only be obtained by means of ordinary electricity, which is alone capable of traversing so imperfect a conductor as the air. We may give to this last experiment a still more striking form, and which assimilates it to the analogous experiments that are made with the voltaic pile, by placing (*fig.* 248.) a series of small bands of litmus and tur-

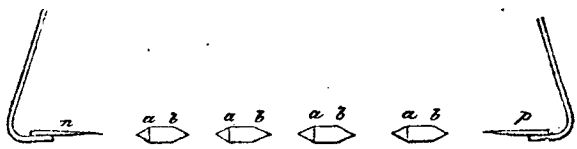

Fig. 248.

meric paper a b, moistened with a solution of sulphate of soda, and arranged at a certain distance from each other, on a plate of glass between metal points p and n, through which positive and negative electricity arrive. All the points of the litmus, as well as those of the turmeric paper, are reddened; which proves that the small layers of air, interposed between the bands of paper, fill the office of conductors and electrodes, as did the wires in *fig.* 245.

The results, which precede, are perfectly in accordance with the theory, that we have given of electrolysis. The elements of an electrolyte, separated by the current, and which are transported by way of successive decomposition and recomposition, arrange themselves at the place where they no longer find an element, with which they can combine; generally it is against the surface of a metal that the deposit takes place; but, we have seen that, in many cases, it may take place against the surface of a liquid, as, for example, in the case of the decomposition of sulphate of magnesia, in which the magnesia stops against the water, placed between the sulphate and the negative pole, and does not reach this pole. It is not then astonishing that the acid of the sulphate of soda, on the one hand, and its alkali, on the other, stop against the surface of the layer of air, interposed between the bands of papers

and the positive and negative poles; since they can neither combine with the oxygen nor with the nitrogen of this air.

But if, as Faraday has proved, ordinary electricity is able to bring about electrolytic decomposition, after the manner of the current of the pile, it is no less true, that it also produces decomposition without transport of elements; for example, in Wollaston's experiments on the decomposition of water. However, we ought to add, that Davy had succeeded in separating the two constituent gases of water, by plunging into it the very fine extremity of a platinum wire, which received the electricity of an electrical machine, and by causing this electricity to be dissipated in the air, by means of filaments of cotton; he collected, as it seems, the oxygen and hydrogen gases separate, but he does not say where that gas was arranged, which was not liberated by the platinum wire. This very doubtful experiment is the only one in which there had been success in obtaining the gases separate, in the decomposition of water, by ordinary electricity; in all others, they were obtained mixed. The explanation of this fact is connected with the necessity there is of distinguishing, in decompositions, brought about by ordinary electricity, those which result from the regular and continuous transmission of electricity, from those which are due to the calorific effect of the spark, acting on the molecules of the liquid, in contact with the wire from which it escapes. The two modes may present themselves simultaneously and in proportions, which depend on the circumstances of the experiment, more favourable to one than to the other. The electrolytic mode is favoured by the very pointed forms of the electrodes, which allow of a continuous escape of electricity, similar to a current; but it is necessary, in addition, that the liquid be a good conductor; this is why it takes place with saline or acid solutions. The non-electrolytic mode is especially presented, when the liquids are imperfect conductors, such as distilled water, or even when they are almost totally insulating, as alcohol and the oils.

We have already seen that Morgan had decomposed alcohol and the oils, by causing electric discharges to pass

through them.* We have also seen that Davy had succeeded, by means of the voltaic spark, produced between two carbon points, plunging in various liquids, in decomposing these liquids, whether they were conductors or not; a proof that the decomposition was not, at least in a great number of the cases, electrolytic, but rather an effect of the heat, liberated between the points. M. Melly has examined more closely this mode of decomposition. He made use of a tube, closed below by means of a cork, through which penetrated a wire, placed by its outer extremity, in communication with one of the poles of a Grove's pile of five or six pairs, and in this tube, filled with the liquid, submitted to experiment, plunged another smaller tube, filled with the same liquid, but closed above by means of a cork, also traversed by a wire, communicating with the other pole of the pile. Contact could be made or broken with the hand, between the extremities of the two wires plunged in the liquid; and at each rupture a spark was produced. It is easy to obtain more than a hundred of these sparks per minute, as soon as the hand is accustomed to this backward and forward motion. Moreover, by means of a small lever put in communication with a toothed wheel, that is set in motion by the hand, we may very easily bring about the making and breaking of contact between the two wires; we may even place the toothed wheel in the liquid, as well as a little metal spring, which presses constantly on the circumference; this spring communicates with one of the poles, the axis of the wheel with the other, and we thus obtain, on turning the wheel, a series of sparks, the number of which depends both upon that of its teeth, and upon the velocity with which it is made to rotate.† By these various processes, M. Melly has succeeded in decomposing olive oil, essence of turpentine, sulphuric ether, absolute alcohol, alchohol at 36°, ordinary naphtha, pure naphtha, sulphuret of carbon, chloride of sulphur, and distilled water,—substances, not one of which could be decomposed electrolytically by the current of the pile employed for producing the spark.

* Vol. II. p. 139.

† *Vide* Vol. I. p. 302., *fig.* 131., a wheel similar to that in question.

Two different facts are observed in general, in these experiments: — the production of a vapour saturated with the liquid, when it is tolerably volatile, and its decomposition. Essence of turpentine does not sensibly vaporise, but there is seen in it a liberation of large gaseous bubbles, which are a mixture of hydrogen and carburetted hydrogen, and a deposit of carbon, which remains in suspension in the liquid; olive oil and naphtha give very similar results to that, which is obtained with essence of turpentine. Alcohol, and especially ether, produce a considerable liberation of bubbles of vapour, in addition of those of gas, which, having arrived at the top of the tube, condense gradually by the cooling of the apparatus. The deposit of carbon is very feeble. Sulphuret of carbon gives no gas; chloride of sulphur gives off a little. In these two liquids, the wires, which are of copper, become grey by the formation of a sulphuret, and carbon in laminæ of a brilliant grey remains in suspension in the former, whilst a little sulphur of a dirty yellow is found in the latter. Distilled water, perfectly pure, and deprived with great care of air, gives rise to a pulverulent deposit, which is protoxide of copper, and to a gaseous liberation, composed for three-fourths of a mixture of oxygen and hydrogen, and for one-fourth of pure hydrogen; probably equivalent to the oxygen of the protoxide of copper. By substituting platinum wires for copper wires in the distilled water experiment, scarcely any gas is obtained, but a very abundant deposit of a black powder, which is nothing else than very divided platinum, as may easily be proved. This experiment demonstrates that, under the influence of the heat of the voltaic spark, platinum has been alternately oxidised and reduced by the hydrogen of the water, which consequently has been decomposed in the same manner as the vapour of alcohol or ether is decomposed in the aphlogistic lamp, by the heat of incandescent platinum. Between two fragments of coke, obtained from the gas-works, a spark is obtained, which decomposes distilled water very well, with production of hydrogen and of a little carbonic acid, the greater part of this acid remaining dissolved in the water.

In all these experiments, the induction spark may be advantageously substituted for the spark of the pile; which produces the same effect, with a much less considerable number of voltaic pairs; one alone is sufficient with a good induction apparatus. However, the effects are more complex, because the induction currents frequently act upon the liquid electrolytically, at the same time as they decompose it by the spark. This explains the anomalous results that Grove has obtained, on decomposing, by means of the induction currents of Ruhmkorff's apparatus *, distilled water, or water slightly or powerfully acidulated. The electrodes were very fine platinum wires, sealed into glass tubes, so that their extremity was embedded in the very end of the tube, without passing beyond it. The gaseous product, accumulated around each point, was a mixture of oxygen and hydrogen, with an excess sometimes of one, sometimes of the other gas; however, when the gaseous mixtures, accumulated around each of the two electrodes, were put together, there was found, after having caused them to detonate, an excess of hydrogen, if the water contains a very feeble quantity of sulphuric acid, and an excess of oxygen if it contains more than the proportion that gives it its maximum of conductibility. When it contains exactly this proportion, there is scarcely any excess of either one gas or the other. We must also remark, that the gaseous volumes are never equal on both electrodes; it is sometimes at one, sometimes at the other, that they are more considerable. If, instead of a point, we take a plate of platinum for one of the electrodes, there is no sensible liberation of gas around the plate, whilst there is some around the other electrode, which has remained a point, as when they were both points. All these effects are of the same kind as those which we have described in a preceding paragraph, with this difference, that, independently of the presence of alternate currents, which act electrolytically, carrying at once oxygen and hydrogen to each of the electrodes, where they undergo a partial, and sometimes

* *Vide* Vol. I. p. 355.

even a total recomposition, as with the plate, the intervention of the spark, which, with M. Ruhmkorff's apparatus, is very powerful, still further complicates the results.

It is probable that the excess of hydrogen, observed in certain cases, is due to the formation of a little oxygenated water, like as that of the oxygen, which occurs when the acidulated water is concentrated, is equally due to the formation of a secondary product, such as sulphuretted hydrogen. The observation, that was made by Mr. Grove, that a blackish powder is deposited, which is divided platinum, when the discharge of Ruhmkorff's apparatus has been allowed to pass for a great number of hours (thirty to forty), not consecutive, by means of a plate and a point serving as electrodes, through the vapours of water arising from distilled water placed in vacuo, is a proof of the alternate decomposition and recomposition of water.

Thus, as M. Masson justly remarks, at the end of certain researches, also made with Ruhmkorff's apparatus, all these results, as well as those, which he himself obtained, confirm the distinction, that we have established between *polar* or *electrolytic* decomposition, and *calorific* decomposition. This philosopher has observed that the decomposition is much more abundant, where the electrode is luminous, for example, at the negative and at that which is terminated in a point, when the other has the form of a ball, because the two modes of decomposition are found united. He quotes several examples of the second mode of decomposition, which he has studied, as M. Melly had already done, by operating upon non-conducting substances. M. Quet, who has made experiments of the same kind as those of M. Masson and Mr. Grove, remarks, that the platinum wire and the glass, by which it is surrounded, are altered and fused, after having been employed for the decomposition of water with Ruhmkorff's apparatus.

It was of importance to prove in a direct manner the existence of calorific decomposition, for it might always be suspected that it was really an effect of electricity and not of the heat liberated by this electricity. It is to Mr. Grove

we are indebted for having demonstrated that decomposition in the case, wherein it is not electrolytic, is truly due to the action of heat. At first he succeeded, after various trials, in decomposing water, by igniting to redness, by means of an electric current, a platinum wire, inserted at the bottom of a tube filled with water and contracted immediately over the wire, so as to allow only the space strictly necessary for the vapour formed by the heat of the wire to ascend, and for the water to redescend (*fig.* 249.).

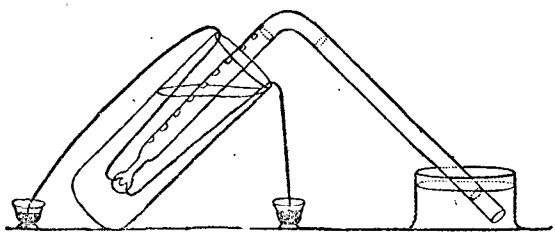

Fig. 249.

Two pairs were sufficient, in order, after the expulsion of the air, that the water may be seen to boil and the wire to become incandescent, in the midst of the vapour; then small gaseous bubbles are seen to separate and to ascend to the top of the tube, whence they are led, by means of its bent end, under a bell-glass; the phenomenon does not take place in a continuous manner, but only by jerks. The gas is a mixture of hydrogen and oxygen. It is evident that the decomposition of the water is truly an effect of the heat of the wire and not of the current, that traverses it; for this current is incapable of being transmitted through distilled water, and no effect is obtained upon separating the platinum wire at its middle, and upon vaporising the water, by means of the flame of a spirit-lamp, applied exteriorly; whilst, on vaporising in the same manner, if the wire is continuous and the current is traversing it, we bring about the formation of a bubble of gas, by filling the tube with water well distilled, and carefully freed of air (*fig.* 250.). Only the bubble must be transferred to another vessel in order to obtain a second. We are not

able, even when the incandescence has been maintained for a long time, to increase the volume of the gaseous mixture beyond a very limited quantity, which is probably due to the fact that, remaining thus in contact with the platinum wire, it detonates and re-forms water. In the experiment of *fig.* 248. it was not the same, because the gaseous bubbles escaped out of the tube, in proportion to their formation. Moreover the mode of operating of *fig.* 250. excludes all idea of electrolytic decomposition, since the incandescent platinum wire is not in contact with the water, but only with a non-conducteous atmosphere of dry vapour.

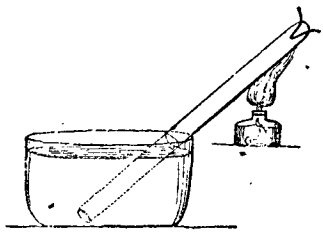

Fig. 250.

After these various essays, Mr. Grove, wishing to exclude the employment of the electric current, even as a source of heat, procured a tube of silver 9½ in. in length, with a diameter of about ½ an inch; at the upper extremity of which was soldered a head of platinum, furnished with a small tube, also of platinum, soldered and closed with gold (*fig.* 251.). The apparatus was filled with water, properly prepared, and the latter was then subjected to boiling, in order to expel the air, adhering to the sides. The tube was then inverted and heated at its upper extremity by the flame of a blowpipe; upon inverting it under water, a small bubble of detonating gas was collected. With a globule of platinum, that was melted at the extremity of a large wire, the decomposition of water was likewise brought about by plunging it in, at the moment, when it attains to the state of fusion. But, in order to obtain a continuous liberation of gas from the body of the water, submitted to the sole action of heat, Grove constructed the

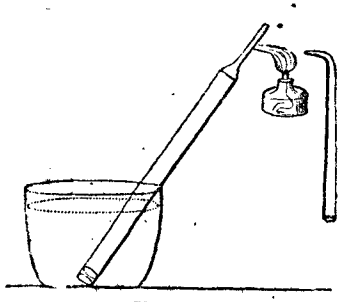

Fig. 251.

following apparatus (*fig.* 252.), in which *a* and *b* are two tubes of silver, $3\frac{1}{2}$ in. in length, and $\frac{3}{10}$ in. in diameter, soldered by two platinum cups to a narrower tube, also of

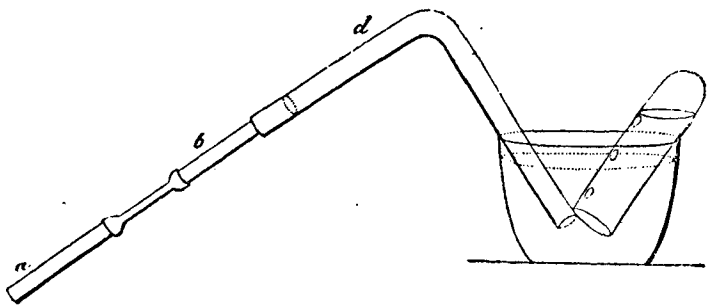

Fig. 252.

platinum. The tube *a* is closed at its extremity, and the bent glass tube *d* is adjusted, by means of a band of bladder, to the extremity of the tube *b*. The whole is filled with water, deprived of air, and after having, by means of heat, brought about the expulsion of the air from the tube *a*, the extremity of the glass tube is plunged into a cup of boiling water. The tube *b* is first heated, by means of a spirit lamp, and then the tube *a*, to complete ebullition; the jet of a gas blowpipe is immediately directed upon the junction tube of platinum. When the temperature has attained as nearly as possible to the fusing point of platinum, gas is liberated at the same time as vapour, so as to fill the apparatus and even to come out of it; it is then collected in a test-tube. It is for $\frac{1}{10}$ a mixture of oxygen and hydrogen in the proportions that form water; the residue is nitrogen, with a little oxygen, which is derived from the air, dissolved in the water.

Thus, under the influence of incandescent platinum, heat alone, without any electric influence, is able to decompose water. This phenomenon cannot be attributed to the catalytic force of platinum; since this force, on the contrary, far from producing decomposition, would bring about combination; it is therefore a veritable direct effect of heat.

The action of electric heat upon gases thus presents some curious phenomena, which it is of importance to study. This also Mr. Grove did, by placing various gaseous substances, successively in a similar tube to that of *fig.* 249. and rendering the platinum wire, which traverses the upper part of the tube, incandescent by means of a voltaic current. The experiments were made sometimes over water, at other times over mercury. Oxygen, nitrogen, hydrogen, carbonic acid, underwent no sensible alteration. Bioxide of nitrogen collected over distilled water, contracted to one-third its initial volume; the residue was nitrogen; and nitric acid was found in solution in the water. The protoxide of nitrogen was decomposed into nitrogen and oxygen, increasing by 0·35 of its primitive volume. Ammonia doubled in volume, the water no longer absorbed it, it was decomposed into its three parts of hydrogen and one of nitrogen. Olefiant gas suffered a slight contraction of volume, accompanied by a feeble deposit of carbon; but the decomposition of the gas was not complete. Chlorine and cyanogen gave thick white clouds, which arose probably from their action upon platinum.

A long time before Grove, philosophers had succeeded in decomposing gases by the electric spark; but, in showing that the same effect is produced by incandescent platinum, Grove has proved that it is truly to the heat of the spark, and not to its being electric, that the phenomenon is due. The protoxide and deutoxide of nitrogen, as well as ammonia, are decomposed by the spark, as well as by incandescent platinum; but the spark decomposes also sulphuretted and phosphuretted hydrogen; the volume of the hydrogen does not change, but sulphur and phosphorus are deposited. Carburetted hydrogen and hydrochloric acid gases are also decomposed; with carbonic acid, an increase of volume is observed, and the formation of a little oxide of carbon, but the decomposition is never complete.

A very remarkable thing is, that this same electric spark, which decomposes compound gases, when traversing them, brings about, in like manner, the combination of elementary gases. The apparatus, that is employed for producing these

combinations, is the same as that, by means of which decomposition is produced. It is a glass tube, the sides of which must be very strong, $\frac{2}{3}$ in. in thickness (*fig:* 253.), closed at its summit, and open at its other extremity; it must be pierced, in the portion, near to the summit, with two small holes, through which two wires of platinum or copper are introduced, which are hermetically sealed in them. The inner extremities of the two wires are opposite to each other, leaving between them an interval of $\frac{1}{10}$ or $\frac{1}{20}$ of an inch; between them the spark is made to pass, by causing the outer extremities of the wires to communicate, one with the inner coating, the other with the outer coating, of a Leyden jar. The tube is generally filled with mercury rather than with water, on account of the soluble gases; then the gases are passed in, whose combination is required to be brought about, care being taken not to introduce sufficient to drive out all the mercury, of which an inch or more must always be left at the bottom of the tube; the latter is plunged by its base in a small cup in which some mercury is placed, that ascends in its interior when the combination of the gases has brought about a diminution of volume in the gaseous mass, as most commonly happens.

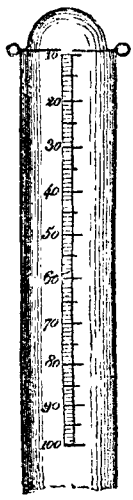

Fig. 253.

The combination, that is brought about most easily, by means of the electric spark, is that of two volumes of hydrogen and one volume of oxygen; it is attended by a violent detonation, which risks breaking the glass tube, if it is not very strong, and the mercury rises rapidly to the top of the tube, to fill the space that had become void by the condensation of the vapour of water, formed by the combination of the two gases. So that the mixture of oxygen and hydrogen, in the proportions that form water, is called explosive mixture. If one of the gases is in excess, it does not prevent the combination, which is always brought about between two volumes of hydrogen and one volume of oxygen, with an

excess of the gas, that is found in too high a proportion in the mixture. However, the gas in excess must not exceed seven times the volume of the explosive mixture, if it is hydrogen, and twelve times, if it is oxygen; there is then no combination. In like manner, if there are more than ten volumes of atmospheric air mixed with one volume of the explosive mixture, the latter does not detonate, under the action of the electric spark. This negative influence of the presence of a third gas is general; but the proportion of the gas, necessary for preventing the combination of the oxygen and hydrogen, varies according to its nature. It is probable that this effect is due to the cooling action, exercised upon the spark by the considerable quantity of the gas, in the midst of which, the explosive mixture is, as it were, drowned; such at least is the case, when the gas in excess is hydrogen, oxygen, or atmospheric air. But it may also happen that this gas itself exerts an action over the oxygen or hydrogen of the mixture; and, in that case, it requires a much less proportion in order to arrest the explosion; this takes place with hydrochloric acid gas, with sulphurous acid gas, and with ammonia.

We should remark, indeed, that in the phenomenon of the combination of oxygen and hydrogen, by the electric spark, the heat of the spark, in bringing about the combination of the first gaseous molecules, that it meets, becomes thus in its turn itself the cause of a great development of heat, which produces the combination of the other molecules, and so on; in such sort, that this combination is, so to speak, instantaneous; a phenomenon, which may consequently be attributed to the great heat, that attends the combination of oxygen and hydrogen. But, when other gases are in question, such as nitrogen and oxygen, for example, which produce but little heat by their combination, a very great number of sparks are necessary in order to their combination, because each spark only brings about the combination of these molecules of the two gases, that it meets directly. Priestley, and after him Cavendish, had observed this, who were the first to succeed in forming nitric acid, by passing a series of electric sparks

through atmospheric air. In order to make this experiment, it is necessary to use a bent glass tube (*fig.* 254.) about an inch in diameter, filled with mercury, except in its upper bent part, in which a little atmospheric air is left, and plunging by its two extremities into separate glass vessels also containing mercury. The mercury of one of the vessels is put in communication with the ground, and that of the other is attached to the conductor of an electric machine; by means of which a current of sparks is made to pass through the air situated in the upper part of the tube. In proportion as the volume of the air diminishes, fresh is introduced. Cavendish, after having operated with this apparatus for a fortnight, half an hour each day, found that the oxygen and nitrogen had combined, in the proportion of seven volumes of oxygen and three of nitrogen, to produce nitric acid; the presence of which could besides be easily detected, either by its action upon blue vegetable tincture, or by the formation of nitrate of potash, when a solution of potash was introduced into the tube.

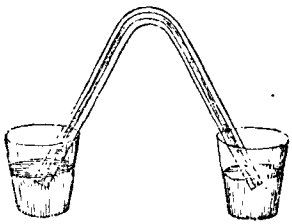

Fig. 254.

The combination of chlorine and hydrogen in equal volumes to form hydrochloric acid, was in like manner brought about by the electric spark; the combination is immediate, as with the explosive mixture, and is attended by a powerful detonation.

Simple gases are not the only ones that form combinations when an electric spark is made to pass through their mixture; new combinations may also be brought about between a compound gas and a simple one. The following is a table, that contains some of the most important results, obtained in this manner: —

2 vols. oxide of carbon and 1 vol. oxygen,	give	2 vols. carbonic acid.
„ protocarburetted hydrogen and 2 oxygen,	„	2 vols. oxide of carbon and 2 vols. hydrogen.

2 vols. protocarburetted hydrogen and 4 chlorine,	give	8 vols. hydrochloric acid; a deposit of carbon.
2 „ bicarbonated hydrogen and 6 oxygen,	„	4 vols. carbonic acid; a deposit of water.
1 „ cyanogen and 2 oxygen,	„	2 vols. carbonic acid; 1 vol. nitrogen.
2 „ hydrocyanic acid and 2½ oxygen,	„	2 vols. carb. ac. 1 vol. nitrogen, and a slight deposit of water.

We see, by what precedes, that the same cause, which brings about the decomposition of a compound gas, may produce a new combination, when this compound gas is in presence of another. One of the phenomena is a consequence of the other in this sense, that the electric spark in distributing by its passage the chemical equilibrium of one gas, facilitates consequently the formation of an entirely new compound. The property of the spark, or rather of the heat, that it introduces into the midst of the gaseous particles, is therefore to distribute the chemical equilibrium, probably by impressing upon the atoms, according to the theory that we have already on one or two occasions laid down, a more rapid motion of rotation than that, which they possess at the ordinary temperature.

It is easy to prove that the property possessed by the spark of bringing about combinations as well as decompositions, is indeed due to heat; we have merely in the apparatus (*fig.* 254.) to substitute for the two platinum points a fine and continuous wire of the same metal, which traverses the tube; on raising it to red heat, by means of an electric current, the same effects of combination are obtained as with the spark.

A circumstance that influences this facility, with which gases combine by the effect of the electric spark, is their density. Grotthus has found that a mixture of chlorine and hydrogen no longer detonates, when it is reduced by rarefaction to a sixth of its density. This rarefaction must be

extended beyond the sixth of its density, in order to make a mixture of hydrogen and oxygen lose its detonating faculty. Rarefaction resulting from elevation of temperature, produces similar effects, which proves that increase of temperature does not compensate for the weakness that results, in the mutual action of the particles, from their greater mutual separation. It would be quite otherwise, if, on heating the gases, they were prevented from expanding, so that their elastic force alone and not their volume, could increase; it is very probable, that in this case the action of the electric spark, for bringing about their combination, would be facilitated. Experiments of this kind have never been made; they deserve to be attempted.

Independently of the chemical effects, that are produced by electricity indirectly upon gases by the heat, which it causes to penetrate into their particles, Mr. Grove has found that it is able to bring about more direct ones, and which seem, to a certain extent, to be electrolytic. It is by employing the induction currents, produced by Ruhmkorff's * instrument, that he arrived at the interesting results, that we are about to describe. The experiments were made by means of an apparatus similar to that of *fig.* 218. A plate of silver was placed upon the support of the bell-glass, and a steel needle was fixed at the extremity of the stem, at a distance of about $\frac{1}{10}$ of an inch from the plate. The induction current was transmitted from the plate to the needle; the medium was air, rarefied to about ·707 in., mixed with hydrogen and a little vapour of water; there was seen to be formed upon the plate, when it was positive, a circular spot of oxide of silver, presenting successively yellow, orange, or blue tints. The direction of the current being reversed, the spot disappeared, and the silver again became perfectly clean; the place that the spot had occupied, might, however, still be distinguished. In rarefied air, without mixture of hydrogen, oxidation took place, whatever was the direction of the current, but it was more rapid, when the plate was positive. In pure rarefied hydrogen, no oxidation took place, but the

* Vol. I. p. 389. *fig.* 150.

surface of the plate finished by becoming slightly unpolished. Nitrogen conducted itself like hydrogen; when it was perfectly pure, there was no trace of oxidation: but, as soon as it was mixed with a little oxygen, then the plate, when it was positive, began to oxidise. For the steel needle were substituted wires of copper, silver, and platinum, without the phenomena being sensibly modified. On substituting for the silver plate, plates of bismuth, lead, tin, zinc, and iron, similar effects were obtained, except as concerns intensity. Platinum alone experienced no effect.

In order better to study the formation of the spots, Mr. Grove, after a few trials, operated, as in the preceding experiments, with a rarefied atmosphere, formed of a mixture of one volume of oxygen and four of hydrogen. The plate was rendered positive, and the lower extremity of the steel needle was brought to distances from the plate, successively equal to $\frac{1}{30}$ in. $\frac{1}{25}$ in. $\frac{1}{16}$ in. $\frac{1}{12}$ in.; and thus were obtained successively the appearances *a*, *b*, *c*, *d*, and *e*, of *fig.* 255.

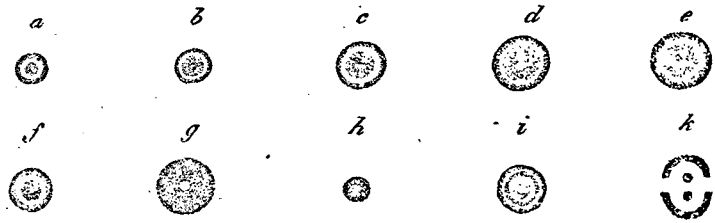

Fig. 255.

The colour of the central spot was greenish yellow in the centre and greenish blue on the edges; then came a ring of silver, not oxidised; then a circular crimson-red ring, tending toward orange on its inner border, and towards deep purple on its outer border. Sometimes in the middle of the central spot, a small circular space was seen, where the silver appeared perfectly bright (*fig.* 255. appearances *f* and *g*), and which was produced, when the plate was negative; this small space was surrounded by a dark and badly defined aureola. The spots *h* and *i* are derived, the first from the discharge transmitted by a platinum wire, enclosed in a glass tube,

after the manner of Wollaston, described above; the second, from the discharge transmitted by a steel needle; the silver plate was positive; the distances, traversed by the discharges, were $\frac{1}{12}$ in.; the receiver contained a mixture of one volume of oxygen and five of hydrogen, under a pressure of ·471 in. Finally, the appearance *k*, is the result of an experiment in which a copper wire $\frac{1}{25}$ in. in diameter had been fixed with wax in a horizontal position at $\frac{1}{30}$ in. above the silver plate; the extremity of the platinum wire was itself $\frac{1}{50}$ in. above the copper wire. It is seen that the interposition of the copper wire has divided the spot into two equal portions, separated by an interval, that remained clear.

The phenomena described by Mr. Grove are analogous in part to those, which I had observed on operating in the same manner, but by means of a pile of high tension *; only they are more numerous and more varied; however, I had remarked the formation of the circular blue spot, even upon a plate of platinum in rarefied air, and its non-appearance in an atmosphere of hydrogen. All these effects appear to me to arise essentially from the high temperature, which the points of the metal conductors suffer, from which the positive electricity comes out, joined to the greater oxidising property which the passage of the discharge developes in oxygen, and the study of which forms the subject of the following paragraph. With regard to the effects of reduction by hydrogen, they are also easy of comprehension; what is least so is to discover why in an atmosphere of hydrogen and oxygen, in which this latter gas is in a small proportion, the plate oxidises, only so long as it is positive, and not when it is negative. When oxygen is more abundant, it oxidises as well as in atmospheric air. Is it that, under the influence of discharges, the oxygen and hydrogen acquired, by the effect of a peculiar polarisation, a tendency to betake themselves, one to the positive electrode, the other to the negative? Mr. Grove would be disposed to admit this opinion, and

* Vol. II. p. 291.

to recognise consequently in gases a species of electro-chemical polarity. I presume rather that the difference of temperature, that is manifested between the two electrodes, joined to the property, that is acquired by oxygen, may explain these oxidations and reductions, that we so frequently see in chemistry to succeed each other easily, by the effect of the slightest variation of temperature.

Mr. Grove has made one other important observation; it is that, when the experiments, which he has described, are made in certain vapours, such as those of phosphorus and others, the electric light is seen to be striped with transverse dark bands; only care must be taken to place the needle at about an inch from the plate. This phenomenon is altogether identical with that, which has been studied by M. Quet, and of which we have spoken in the preceding Chapter.* Up to what point is it connected with a chemical effect, exercised upon the atmosphere of vapours by the discharge, either indirectly by heat, or directly by electrolysis? This is impossible to say, in the present state of the science. What is very remarkable is this coincidence between the formation of rings alternately brilliant and dark, upon the surface of the electrodes, and the appearance in the atmosphere of vapours, of bands, in like manner, alternately luminous and obscure; which would seem to indicate, equally in both cases, a kind of effect of interference, and consequently a connection between the two sorts of phenomena.

We shall not terminate this paragraph, without saying a few words on a mixed phenomenon, which is due at once to the chemical and to the calorific effects of dynamic electricity; I refer to the incandescence of wires that serve as electrodes, in liquids and in elastic fluids. Hare was the first to observe it in a very striking manner, by plunging into a solution of chloride of calcium, an iron wire as a negative electrode, and a finer platinum wire as a positive electrode; the latter melted into globules; on changing the places of the

* Vol. II. p. 275.

wires, the phenomenon did not occur. Mackrell obtained effects of the same kind with wires of different natures plunged into diluted sulphuric acid. He succeeded in raising to a red heat in the liquid, iron and copper wires two inches in length; the effect depended upon the position of the wire in respect to the positive or negative pole, and on the fact, that one of the two was immersed first or second. When the two electrodes were formed of plates of platinum, the positive electrode was greatly heated and presented from time to time along its section a bluish light; when the negative electrode was placed last in contact with the liquid, it gave no light, but produced small explosions.

Grove made some interesting experiments upon this subject with an enormous battery of 500 pairs, which Mr. Gassiot had had constructed. A platinum plate, forming the positive electrode of the battery, was plunged into a cup of distilled water, the temperature of which had been raised. The negative electrode, formed of a platinum wire, was brought near, so as to touch the surface of the water for an instant, and was immediately drawn back to a distance of about $\frac{1}{4}$ in. as soon as the discharge had taken place; the extremity of the wire entered into fusion, and the melted platinum remained, as it were, suspended in the middle of the surrounding air, giving off an intense light, throwing out sparks in directions contrary to that of the water, and was not detached from the wire, until it was shaken off. The water in a state of vapour was decomposed, for the positive electrode liberated gases; and the molecular action exercised upon the negative platinum altogether resembled the currents, that are observed upon the surface of mercury, when it is rendered negative in an electrolyte. However, as the gases produced were not collected, it is impossible to decide whether the decomposition is a veritable electrolysis or simply an effect of the high temperature of the platinum; which latter appears the more probable.

M. Quet, on his part, has succeeded, by means of a pile of forty large Bunsen's pairs, in obtaining a vivid light upon platinum electrodes, by decomposing water, either acidulated, or holding potash in solution. The platinum wire is not in-

candescent, but surrounded as it were with a sheath of light, which seems to separate it from the neighbouring water. In diluted sulphuric acid, the light of the negative electrode is violet and that of the positive is red; in solution of potash, that of the negative electrode has a beautiful rose tint. When the luminous phenomenon is produced, the decomposition of the water, which was very vivid, is much reduced; it is revived, as soon as the illumination ceases. The negative electrode is in general the one, that is the more easily illuminated. With a comparatively feeble pile, we obtain, by cautiously bringing near to the surface of the liquid, in which the positive electrode is plunged, the extremity of a platinum rod serving as the negative electrode, a violet light around this extremity with a slight noise of crepitation; it is essential that the rod shall merely touch the liquid, or shall dip into it only $\frac{1}{25}$ of an inch.

Latterly, again, M. Van der Willigen, in operating with diluted and concentrated sulphuric acid, or with solutions of chloride of sodium, sulphate of potash, &c., has remarked the influence that may be exercised on the calorific or luminous effect, manifested by one of the electrodes, by the fact that it is plunged first or last; he was able to satisfy himself that these very complex phenomena, in which wires sometimes became incandescent, sometimes are simply surrounded by a luminous aureola, are due to its happening that, in certain cases, they are not in contact with the liquid, or account of their elevated temperature, which gives to the surrounding liquid the spheroidal state. In other cases, the products of decomposition themselves suffer an incandescence or a combustion, which imparts to the light a particular tint. Finally, the heat itself combines with the electrolysing action, in order to decompose the liquid conductor, what may itself, as well as a solid conductor, form the electrode of a voltaic arc. Moreover, all these effects would have need of being analysed with much more care than has been devoted to them, in order that we may be enabled fairly to distinguish the part of the influence, which is due to the chemical action of the current, from that which is exercised by the heat itself,

that is developed by the current, whether in producing the arc or in heating wires; it would appear very probable that we should not find in it any peculiarity, that was not the consequence, easy to be anticipated, of the phenomena, that we have described, either in this or in the preceding Chapter.

Production and Properties of Ozone.

Before terminating the study of the chemical effects of dynamic electricity, it is necessary to devote a few moments to the examination of one of the most remarkable; I refer to the odour, half sulphurous, half phosphoric, which accompanies the liberation of electricity in the air, by ordinary electrical machines, and which is found at the positive electrode, when water is decomposed, by means of a powerful electric current. It is to M. Schœnbein that we are indebted, by his profound studies upon this particular point, which had escaped the attention of physicists, for having put them in the way, which has led them to discover the nature itself of this phenomenon.

Priestley, Cavendish, and Van Marum had plainly remarked that gases undergo considerable modifications, consequent on the passage of electric sparks, and, in particular, they had pointed out, as we have said, the formation of nitric acid, when the gas was a mixture of oxygen and nitrogen, such as is presented by the atmospheric air. Van Marum, however, by causing a succession of electric sparks to pass in a tube full of oxygen, $5\frac{1}{2}$ inches in length, between a metal conductor, situated at the top of the tube, and a mercury bath, situated at the lower part, had remarked that the gas had acquired a very powerful odour, which he stated was that of the *electrical machine*. Moreover, on operating with a narrow and shorter tube, he remarked, that the mercury was powerfully oxidised at its surface, and that the volume of oxygen had diminished; but these effects might be attributed to the formation of nitric acid, seeing that nothing proved that the oxygen was very pure and that it contained no nitrogen.

M. Schœnbein, sixty years subsequently, being desirous

of explaining the cause of the odour, that accompanies the voltaic decomposition of water, observed that this odour is manifested at the positive electrode, only so long as this electrode was not oxidisable, namely, when it was platinum or gold. He proved that the odour still exists, when the mixed gases are collected; and that it may be preserved as long as we please, when the oxygen, or the mixture of oxygen and hydrogen, that possesses it, is enclosed in well-stoppered bottles. All electrolytes are not equally adapted to developing the odorous principle; distilled water and solutions of acids or of oxygenated salts liberate it easily; but it is not the same with concentrated nitric acid, and with solutions of chlorides, bromides, iodides, nor with that of the sulphate of protoxide of iron. In order to cause the odour to disappear, we have merely to throw into the flask, in which the gas impregnated with it is contained, a few pinches of powdered charcoal, filings of iron, zinc, tin, lead, or arsenic, as well as of bismuth or antimony in powder, or even a few drops of mercury. The same effect is produced by small quantities of aqueous solutions of the chlorides of iron or tin, of sulphate of protoxide of iron, or of a few drops of nitrous acid. Mere elevation of temperature produce the same effect; and so the odour is not developed when the electrolytic liquid is heated, even when, as I have observed, it is the current, by which the decomposition is brought about, that heats it. I have also remarked, that although generally a powerful pile is necessary in order that the odour, attending on electrolysis, may be manifested, it may be obtained with a very feeble current, on the precaution being observed of taking for the positive electrode, in acidulated water, a platinum wire inserted in a glass tube, according to Wollaston's method (*fig.* 239., p. 413).

An important property of the gas, inpregnated with the odour, and which it ceases to possess, as soon as this odour is removed from it, is the faculty it possesses, of polarising negatively wires or plates of platinum or gold, that are placed in it, namely, of impressing upon them, on being plunged into conducting water with a similar wire or plate, but which

has not been in contact with the odorous principle, the property of developing an electric current, of which they are the negative element.

Schœnbein has observed that the same property might be given to platinum and to gold, by receiving on very clean plates of one or other of these two metals, the electricity emanating from the blunt extremity of a wire, in communication with the conductors of an electrical machine, and placed at a distance of about an inch from the plates. It is of little consequence whether it is one or other of the electricities, that comes out from the conductor; the effect upon the plate is the same, but the phenomenon is not manifested, if, the metal being in direct communication with the conductor, the electricity comes out from the plate, instead of being received by it. Platinum and gold immediately lose their polarity under the action of heat, or if they are plunged for a few moments in an atmosphere of hydrogen; only, in this latter case, these metals may acquire an opposite polarity, when they are left too long in the hydrogen.

The odour always attends the polarisation of the metals: thus, no odour nor polarisation is observed when the points, from which the electricity comes out, are heated or are surrounded by a layer of water; it is sufficient even to envelope the metal point with a little piece of cloth, moistened with distilled water, in order to prevent the production of the odour.

These first observations already establish a great analogy between the odorous principle, developed in the electrolysis of water, and that which is produced by the electricity of ordinary machines; it also appears probable that it is identical with that which is manifested in clouds, and particularly in the neighbourhood where a lightning flash had occurred. It is, moreover, evident that it is gaseous, and that it is a product of the action of electricity upon the ambient medium, which can be only oxygen, nitrogen, or the vapour of water; with M. Schœnbein, we will call it *ozone*, without anticipating for the moment anything as to its chemical nature, simply on account of the peculiar and very decided odour, that it possesses.

Led by analogies deduced from the odour, M. Schœnbein

discovered a chemical method of preparing ozone. This method consisted in placing a piece of phosphorus in a vessel, filled with common air. If the temperature is sufficiently elevated for the phosphorus to become luminous, the air of the flask soon acquires an odour of ozone, very distinct from that of phosphorus, or rather from the phosphoric acid, that is liberated at the commencement. This air presents the same phenomena as if it had been submitted to the action of electricity, namely, that the platinum and gold plates are polarised negatively, and that it loses its properties, when filings of iron or of another oxidisable metal, are agitated in it. Phosphorus, in pure and very dry oxygen, in which it does not become luminous, does not produce ozone; it is necessary, for this production, that it be phosphorescent; and, for this purpose, that it be placed in a mixture of oxygen and nitrogen, and at a temperature which is not too low.

Independently of these fundamental properties, ozone, whatever be the manner in which it is prepared, possesses a great number of others, of which the following are the principal. It acts upon vegetable colours, like chlorine; namely, it destroys and bleaches coloured papers, that are plunged into gases that contain it. And this takes place equally whether the ozone has a chemical or an electric origin; and whether this electric origin arises from electrolysis, from the action of the electrical machine, or from atmospheric electricity. It is the same with all the chemical effects of ozone, and in particular with one of the most remarkable, namely, with the action that it exercises over iodide of potassium, which absorbs it, liberating iodine, which is rendered sensible by the change of colour. In effect, if starch paste is mixed with a small quantity of a solution of iodide of potassium, and a slip of paper is plunged into it, a test is obtained for ozone, which greatly surpasses in delicacy the best galvanometer, or the most delicate sense of smell. A quantity of ozone, too feeble for polarising a metal in a sensible manner, or for being detected by the smell, is yet sufficient to make the test-paper blue in a decided manner.

We cannot follow M. Schœnbein in the detailed study, that

he has made of the various chemical reactions of ozone, both upon inorganic substances, as well as upon organic compounds. Without entering into further details, we may merely say that ozone, in a general manner, always comports itself, and more particularly in respect to compound gases and to simple bodies, absolutely like chlorine or bromine.

Iodide of potassium enables us to discover the most feeble traces of ozone in the atmospheric air. We have merely to suspend in the open air little slips of filtering paper moistened with a mixture of the iodide and starch, and commonly, at the end of a few minutes, they are seen to become blue, whilst they are not at all coloured in vessels hermetically sealed and filled with air. Ozone is also found in the water of a storm; for this water imports itself exactly like distilled water, in which ozone has been dissolved. It is simply necessary, in these two cases, in order to liberate the ozone, to pour a little sulphuric acid into the water; it immediately colours blue the paste of iodine and starch. It would appear that ozone forms with pure water a compound, which is destroyed by the presence of sulphuric acid. We can exactly communicate all the properties of the water of a storm to distilled water, placed in a cup and put into communication with the ground, whilst it is exposed to the action of an energetic electric brush, and which diffuses a powerful odour. It is necessary that this exposure should endure for at least half an hour, in order that the water may be sufficiently ozonised.

Without dwelling upon the divers hypotheses, that have been advanced upon the nature of ozone, we shall pass on at once to the experiments of M. Marignac, which have been the first to solve the question in a peremptory manner. This learned chemist has first demonstrated that the presence of nitrogen was not, as M. Schœnbein had at first thought, indispensable to the production of ozone. In effect, on decomposing water, acidulated with sulphuric acid, in an apparatus accurately preserving vacuum, and into which no trace of air could enter, after the experiment had gone on for several days, and the fourth part of the water had been decomposed, the odour of ozone was the same as at the first instant; it was merely ne-

cessary to take the precaution of retaining the flask, in which the decomposition takes place, at a low temperature.* Furthermore, M. Marignac has found that the most convenient method of obtaining ozone consists in directing a current of air, by means of a gasometer, through a tube, about a yard long and a quarter of an inch in diameter, containing in its length a series of sticks of phosphorus. He has proved, by means of this apparatus, that neither pure oxygen nor nitrogen produces ozone; but that oxygen mixed, not only with nitrogen, but even with carbonic acid and with hydrogen, developes it. Perfectly dry atmospheric air does not liberate any; the phosphorus, in this case, is covered with a white crust, and does not become phosphorescent; now, its phosphorescence is a condition necessary, in order to there being a production of ozone.

M. Marignac, on submitting ozone to different tests, remarked, first, that it is destroyed in passing through a tube heated to 600° or 700°; that it undergoes no alteration on the part of water, concentrated sulphuric acid, ammonia, and baryta water; but it is absorbed with the greatest facility by dissolved iodide of potassium; the liquor becomes yellow; a portion of iodine is set at liberty, and drawn on by the current of air. When all the iodide is decomposed, the odour of ozone appears, and the liquor again becomes colourless, and contains nothing besides iodate of potassium, mixed with a little carbonate. Metals, in like manner, absorb ozone; thus on making ozonised air pass through a small tube 4 or 5 in. in length, filled with pure and porous silver, it is found that this air completely loses its odour and its properties, and that

* M. Soret more recently has found that the quantity of ozone obtained by the electrolisation of acidulated water, increased in a very great proportion with the reduction of temperature. Thus, on surrounding the voltameter with a frigorific mixture of ice and sea-salt, and, still better, chloride of sodium, the gas that escaped from it was so much ozonised, that it attacked and rapidly pierced the caoutchouc tubes, which connected the drying tubes, that it had to traverse. On dosing the ozone by means of a known solution of arsenious acid, which, like chlorine, possesses the property of transforming it into arsenic acid, M. Soret has found a proportion of ozone rising to nearly 0·005 of the volume of oxygen, by cooling the voltameter sufficiently for the temperature to be still 19·4 at the end of the experiment; this same proportion was at most 0·003, when the voltameter was not cooled.

the silver is transformed into a matter, which has all the characteristics of oxide of silver; but the presence of moisture is indispensable. If the ozonised air is completely dried, by its passage through several tubes, filled with pumice-stone impregnated with sulphuric acid, it attacks neither silver nor copper, nor even zinc, and it no longer loses its odour.

These experiments, and others besides, no longer allow us to chose between two hypotheses on the nature of ozone; one, that it is a new compound of hydrogen and oxygen, susceptible of being transformed with great facility into oxygen and water, and capable of giving off its oxygen to a great number of bodies; the other, that it is only a peculiar modification of oxygen, in consequence of which this gas acquires, with a peculiar odour, the property of combining with bodies, upon which it is without action in its ordinary state. This last hypothesis is the one that M. Marignac and I were led to admit, as the result of experiments, in which we endeavoured to expose to electric discharges various gases, that we caused to arrive successively in a glass tube 6 in. in length, and $\frac{1}{2}$ in. in diameter, communicating on one side with the apparatus, intended to produce the current of gas, that we were desirous of studying, and on the other with a flask, in which we might examine the properties which these gases had acquired. Two platinum wires penetrated by the extremities of the glass tube, and terminated in its interior at nearly half an inch from each other. One of these wires was placed in communication with the ground, the other with the conductor of the machine; it was a matter of indifference whether the charge was made by a succession of sparks, or by a continuous and invisible current. The formation of ozone was easily detected, by means of its odour, and its action on paper impregnated with starch mixed with iodide of potassium. Now, the experiment made with ordinary air, perfectly dried, gave a development of ozone, as great as when the air was moist; ozone was in like manner developed with the greatest facility in oxygen perfectly pure and dry; such as is extracted from chlorate of potash purified and previously melted. No ozone was formed in pure carbonic

acid gas, whether dry or moist, but some was produced, as soon as a very small quantity of air or of oxygen was mixed with the carbonic acid.

M. Schœnbein, as the result of fresh researches, has himself come to adopt the opinion, to which M. Marignac and I had been led, that ozone is only a modification of oxygen, by which its chemical affinities are exalted; for renouncing the opinion that it is a peroxide of hydrogen, he dwelt especially upon the fact that a mass of ozonised air, on traversing a tube heated to near 600°, is de-ozonised, without production of water. He also demonstrated that, treated by an alkali, ozonised air always produces a nitrate, on account of the facility that oxygen, in the state of ozone, possesses of combining with nitrogen.

MM. Frémy and E. Becquerel have also, as the result of long and rigorous researches, succeeded in demonstrating that ozone is an allotropic modification of oxygen, due to electricity. In order to obtain ozone, they have employed successively the decomposition of water by electric currents; the action upon air and upon oxygen of sparks, obtained by the breaking of a voltaic circuit; of those produced by an induction apparatus; and, finally, of those, drawn from ordinary electrical machines. The first method produced too little ozone. Voltaic sparks are accompanied by a liberation of heat, which destroys the ozone, in proportion as it is produced; it is the same, although in a less degree, with the induction sparks; they were, therefore, compelled to renounce these methods of obtaining ozone, in order to recur to the action of the sparks of ordinary machines. Both philosophers recognised that oxygen, whatever be the source, whence it is derived, is susceptible of being ozonised; and that oxygen, which has been de-ozonised, by traversing iodide of potassium, may again be ozonised. But the most important, among the points, which they have established, is that a given quantity of oxygen may be entirely converted into ozone; and that if, in the previous experiments, they had never succeeded in ozonising more than a portion of the gas, submitted to experiment, it is that probably the electric spark, by its calorific action,

destroyed in great part the effect of the ozonisation, that it had produced upon the oxygen. In order to avoid this inconvenience, it was necessary to absorb the ozone, in proportion as it was formed; with this view some pure oxygen was introduced into a eudiometric tube, itself placed upon a solution of iodide of potassium; the gas was subjected to the action of electric sparks passing between platinum wires fixed at the top of the tube; there were several similar tubes, the diameters of which were $\frac{1}{10}$ in., and the length nearly 5 in.; the sparks were about $\frac{1}{2}$ in. in length. The oxygen was absorbed in a regular manner by the action of the electric sparks; after three hours of electrisation, the liquid had risen $\frac{3}{4}$ in. in the interior of the tube; the absorption was in general proportional to the time of electrisation; on continuing the experiment for a sufficiently long time, the oxygen might be made to be completely absorbed by the iodide of potassium. A very curious result was obtained, by causing the same quantity of electricity to pass in two tubes placed one after the other, and similar in every respect, except that, by the arrangement of the platinum wires, the sparks were an inch in length in one, and only $\frac{1}{5}$ in. in the other; after three hours of electrisation, the absorption of oxygen in the former was double what it was in the latter, which proves that, for a like quantity of electricity, which traverses a similar mass of gas, a long spark produces more effect than a shorter one.* A plate of silver, introduced into a eudiometric tube placed over water and filled with pure oxygen, absorbed the electrised oxygen, like iodide of potassium, but more slowly than it; and the absorption took place until the complete disappearance of all the gas. Mercury, under the influence of moisture, has produced the same effect, and is in like manner oxidised.

Amid the multiplied experiments of MM. Frémy and E. Becquerel, we will in addition cite the following; in which, having introduced pure oxygen into narrow tubes, one con-

* Might it not be possible that this result is due both to the fact that the long spark acts in the same time upon a great number of particles, and that, on the other hand, it developes less heat than the short one?

taining moist iodide of potassium, and the other a small plate of silver covered with moisture, they caused a series of electric sparks to pass into the interior of these tubes, after having closed them at the lamp, at their two extremities. The tube containing the moist silver was electrised for four days, at the rate of six hours per day, namely, for twenty-four hours in all; the plate was covered with oxide of silver; and on then breaking one of the extremities of the tube under water, an absorption was proved equal to two-thirds of the volume of oxygen, submitted to experiment. The absorption was total in the second tube, containing the iodide of potassium; even, after eighteen hours of electrisation, the spark, which had much brilliancy, was scarcely visible; a proof that the vacuum in the tube was nearly complete; after forty-eight hours, the tube having been broken at one of its extremities under water, the latter immediately rushed into it, and totally filled it.

It, therefore, appears now to be well established, that electricity, in acting upon oxygen, impresses upon it properties, which it did not possess before being electrised, and which are manifested by a peculiar odour, and by an exaltation in its chemical activity. It is very probable that the action of phosphorus is also an electric action, arising from a liberation of electricity, which must accompany the combination of a part of the oxygen with this body, and which is manifested by its phosphorescence.

With regard to the nature of the action, that electricity exercises over oxygen, in order to ozonise it, this is still a mystery; it might not be impossible that it consists in insulating the atoms of oxygen from each other, which in the ordinary state might be grouped so as to form molecules, composed of a greater or less number of these atoms. We could conceive that thus insulated, the atoms might have a greater chemical activity, than when they are agglomerated. This might be the *nascent state*. This property of oxygen of forming molecules composed of atoms grouped together, might very well be reconciled with the magnetic virtue possessed by this gas, and which it is alone in

possessing.* But it is premature to venture upon hypotheses, on which experiment alone can decide; and to which, moreover, we shall be called again to direct our attention in the sequel.

We shall confine ourselves to pointing out two rocks upon which physicists have fallen and run the risk of falling, who have been occupied with ozone; one is, in believing that they see in it a nitrous compound, which is due to the difficulty there is in excluding the presence of nitrogen, which in effect is itself sufficient to bring about the formation of such a compound; the other, is in believing that ozone is an oxide of hydrogen on account of this water, which oxygen, although perfectly dried, may still deposit on being deozonised. M. Baumert had thought he might even conclude from this a difference between ozone, obtained by the electrolysation of water, and that which is derived from the electrolysation of oxygen by sparks, admitting that the latter is indeed an allotropic modification of oxygen, but that the former is an oxide of hydrogen. However, it is easy to explain the presence of a small quantity of moisture in the oxygen, that is derived from the electrolysation of water, by the facility with which hydrogen may mix with it, and consequently form water, especially when it is thought that the production in question is of merely 0·07 grs. of water, in operations that have continued without interruption, one, six, the other, eight days.

We must not dwell upon the consequences that result from the production and the properties of ozone in the electrochemical decomposition of substances, of which oxygen is one of the elements. We shall point out one alone, which is perhaps the most important, namely, the formation of oxygenated water, in the electrolysis of acidulated water, and, consequently, of the inaccuracy that results from it in the indications of chemical voltameters. M. Meidinger has studied the circumstances which facilitate this formation in facilitating that of ozone; it is first the degree of concentra-

* Vol. I. p. 468. and following.

tion of the acidulated water; with sulphuric acid of the density 1·4, he obtained in 6 minutes 245 measures of hydrogen for 87 of oxygen; whilst with acid of only 1·07 of density he obtained in 19 minutes the required proportions of 244 hydrogen, and 122 oxygen. Then there is the form of the positive electrode; on taking for this electrode a wire, instead of a plate of platinum, he obtained only 40 measures oxygen for 253 of hydrogen. Then there is finally the force of the current and the reduction of temperature; two circumstances that very notably diminish the proportion of oxygen in relation to that of hydrogen. This greater or less diminution in the required quantity of oxygen is accompanied by an odour of ozone, which indicates the production of this body; but it is easy to prove, on examining the liquid, that the greater part of the liberated ozone has been employed to form the bioxide of hydrogen, which is found in the state of solution in the electrolytic liquid. The presence of this bioxide renders this liquid very unfitted for using in voltametric experiments; for it then gives a less proportion of hydrogen, than that which is liberated in another voltameter, charged with a liquid that has not been used, and that is placed in the same circuit. It is therefore necessary to change the liquid of the voltameter, when it has been used for a certain time, or carefully to boil it, in order to expel the bioxide of hydrogen. In general, if we desire that the indications of the voltameter shall be exact, namely, that the gases shall be truly liberated in the rigorous proportions, it is necessary, in order to avoid the production of ozone, to make use of a water rather feebly acidulated (1·1 in density), to cause the hydrogen to be liberated on a wire, and the oxygen on a plate of platinum which must not be too small.*

* *List of the principal works relating to the subjects treated of in this Chapter.*

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Cruikshanks.—Decomposition of salts. *Bibl. Brit.* t. xv. p. 23.

Davy.—Chemical power of voltaic electricity, &c. *Bibl. Brit.* t. xxxiv. pp. 16. and 397.; t. xxxvi. p. 391.; t. xxxix. p. 3.; t. xli. p. 33. *Ann. de Ch.* t. lxii. p. 172.; t. lxviii. p. 203.; t. lxx. pp. 189. and 225.

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CHAP. IV.

PHYSIOLOGICAL EFFECTS OF DYNAMIC ELECTRICITY.

Nature of the Effects that are exercised upon Organised Bodies by Dynamic Electricity.

We have seen that a frog, properly prepared, suffers a shock, when it is traversed by even a very feeble electric current. Even, before this experiment of Galvani's, it was known that electricity exercises a special action over organised bodies, both vegetable as well as animal; the electricity furnished by electrical machines, had even been employed as a curative means in cases of paralysis; but it is chiefly since the discovery of the pile, that we have been enabled to study with more precision the physiological action of dynamic electricity. This study is very difficult and delicate, as is everything touching on physiology, on account of the ignorance in which we still are, as to the mode of action of the vital force, which presides over all phenomena of this kind. Furthermore: does this electricity act in a direct manner? or does it only exercise an indirect action, by bringing about calorific and chemical effects, which might themselves be the causes of the phenomena observed? And, in effect, when traversing organised bodies, it necessarily produces in them heat, and chemical decompositions; in degrees, it is true, more or less sensible, but yet for the most part appreciable. Now, this heat and these decompositions, may themselves give rise to effects, which might erroneously be attributed to the direct action of electricity. Thus Davy, having submitted a laurel leaf to the action of a pile of 150 pairs, employing it to connect together two vessels filled with pure water, into each of which was immersed one of the

electrodes. This leaf assumed the same appearance as if it had been exposed to a temperature of 500° or 600°; it became brown, and was even shrivelled; the green colouring matter, as well as resin, alkali, and lime, had been transported into the negative vessel, whilst the positive contained a clear liquid, that had the odour of the peach blossom, which was hydrocyanic acid. A plant of mint, also employed as a conductor, gave, after a prolonged action, results of the same kind; but, if the action does not continue too long, the plant is able to recover its original state. It is evident that the electric current acts upon vegetable and animal matters, as upon electrolytes, and that it must necessarily, at the end of a certain time, bring about the disorganisation of the organised body, as would every other calorific or chemical action.

In the same manner may be explained the apparent influence of electricity upon germination and fermentation. It follows, from the numerous trials, that have been made upon the former point, that static electricity exercises no influence over germination, as Ingenhouz had very well demonstrated, by showing that the errors into which we had fallen in this respect were due to our not having had regard to important circumstances, such as the presence of water, of light, &c. With regard to the influence of dynamic electricity, which is real in some cases, it is easy to prove that it arises from an indirect action, namely, from that, which is exercised by the products of decomposition, and in particular by that of oxygen and the acids, on the one hand, hydrogen and the alkalis, on the other hand, upon seeds placed at one or the other pole, whether in the water, or in moist earth. Thus, whilst oxygen facilitates germination toward the positive electrode, it also very frequently happens that the acid, which is equally liberated at this electrode, produces the contrary effect, by destroying the seed, whilst it is seen to grow at the negative electrode, where an alkaline base is accumulated; this is the result of the numerous researches upon this subject by M. Becquerel and M. Matteucci. But it is not impossible, as we shall see in the Fifth Part, that the electricity developed, even in the act of germination, plays

a part, secondary it is true, in this physiological phenomenon. It is the same with the fermentation that M. Gay-Lussac succeeded in bringing about in the juice of the grape, preserved protected from the air, by plunging into it two platinum wires, communicating respectively with the poles of a powerful pile; it is evident that oxygen, due to electrolytic action, was the cause of the fermentation, since nothing more was necessary than to introduce a small portion of this gas, in order to bring about the production of the phenomenon, which cannot commence in a medium in which there is no oxygen. Finally, the coagulation of albumen around the negative electrode, observed by M. Lasaigne, is also the result of the presence at this electrode of acids, arising from the decomposition of certain salts.

We shall not, therefore, dwell longer upon these indirect effects of the electric current, we shall confine ourselves to two remarks; first, that we must take it into account, when occupied with the direct effects, and when especially we arrive at the study of the electricity itself, produced by actions either purely physiological, or chemico-physiological; secondly, that the chemical influence of dynamic electricity upon the organic products would in itself be the subject of a very interesting study, on account of the characters peculiar to this kind of compounds, which cause them to differ in so decided a manner from inorganic compounds, on account of the life that has presided over their formation. Unfortunately, the number of researches hitherto made on this particular point, which is more in the jurisdiction of organic chemistry than of electricity, is very limited; we shall endeavour to make known the small number of results, that have been obtained, when we shall be occupied with electrochemical applications.

Let us, therefore, now pass on to the phenomena themselves, to which the direct action of electricity upon organised bodies gives rise. Vegetables, although much less excitable than animals, are yet so within certain limits. Thus, either the *Mimosa sensitiva* or the *Mimosa pudica* present movements, when the electric current is made to pass through their

branches and leaves, by means of small plates of lead or tin, with which they are covered, in some parts of their surface. The simple communication of the coatings together, without the intervention of the pile, is not sufficient; but, with the passage of electricity we see, in the *Mimosa pudica* especially, a minute after the establishment of the current, the leaves, especially those that are coated, bend upon their branches; then the same effect is produced successively upon other leaves here and there, in several parts of the plant. Giulio, to whom we are indebted for these experiments, has found that, in the *Mimosa asperata*, in which the natural irritability is less decided, the irritability produced by electricity upon its knots, its leaves, and its petals, is much less than upon the other two species of mimosa. The *Hedysarum gyrans*, and other plants, remarkable by the movements, that are presented by their follicles, suffer no influence on the part of dynamic electricity.

We therefore perceive that the physiological action of this agent upon the vegetable kingdom is of very little importance; or at least that our knowledge in this respect is very limited. However, there exists yet one plant, upon which very remarkable effects of electricity have been observed, it is the *chara*, which, as we know, presents a very curious physiological phenomenon, namely, a circular movement of the globules and of the lymph; these globules, directed from below upwards, descend again the moment they encounter a knot, which opposes their motion, in order to reascend, and so on; on taking away the diaphragm, which forms the knot, the globules escape by the opening, and disseminate themselves in the water. MM. Dutrochet and Becquerel, on causing an electric current of greater or less force to pass in a stem of the chara, sometimes from above downwards, sometimes from below upwards, have remarked that this transmission produces in the first instance, a torpor in the movement of the globules, the intensity of which depends upon the force of the current, and which is independent of its direction, but which is the same on ascending and descending motions. When the motion of the lymph has been arrested, it recommences gradually, without the current

ceasing to pass, and it recovers the velocity which it had primitively; the duration of the stoppage depends upon the intensity of the current; it may extend to several hours, if this intensity is sufficiently great; but the passage of the electricity produces no disorganisation in the plant, since a repose of greater or less duration restores to it its natural faculties. Elevation of temperature produces upon the chara effects analogous to those of the passage of the current. Setting out from 32°, the circulation of the chara is accelerated in proportion as the temperature rises; at 65° or 66°, it is very rapid; it diminishes to 80°, where it is very much reduced; it then again increases to 113°, when it ceases entirely, or it is not able to recommencé, the plant undergoing at this temperature a disorganisation, which destroys the rotatory movement of the globules. We may therefore believe that it is to the heat, which it developes in traversing the chara, that the current owes its effect; but it never produces acceleration, as the augmentation of temperature brings about; and, on the other hand, heat does not produce a stopping, like that which takes place with electricity transmitted. It therefore appears more probable, that the influence of the current upon the circulation of the chara arises from the new arrangement, which it compels the molecules of the vegetable to assume, by polarising them; a polarisation which, when it is followed by a very powerful decomposition, may disorganise the vegetable; but against which, however, the vital forces, that produce circulation, contend with sufficient advantage, that the organic molecules, deranged from their natural position of equilibrium, are able to recover their primitive properties. The action, by which the rotatory motion is brought about, overpowering that of the current, the latter continues to pass without disturbing the motion; but the conflict ceases, when the current possesses a sufficient intensity; on the other hand, the vital forces, after having made efforts, which, moment by moment, exhaust them, recover their faculties, after a certain time of repose, when once they cease to be exposed to the action of electricity. We therefore see, that there are very notable differences

between heat and the current, in respect to the manner in which their action is exerted, which enables us to conclude that electricity acts in this class of phenomena in a manner that is peculiar to itself.

But it is chiefly upon animals that the direct action of electricity has been proved and studied. The most striking manner of demonstrating this is to prepare a frog after Galvani's plan (*fig.* 256.), by cutting it in the middle of the

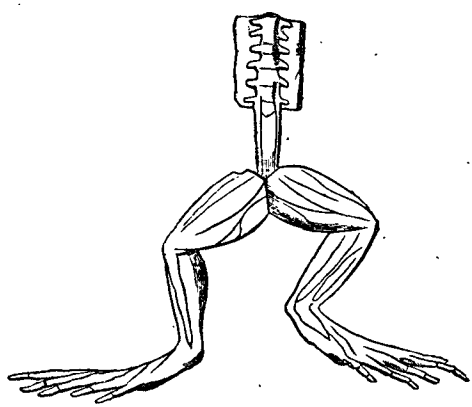


Fig. 256.

body; then, after having rapidly skinned it, the point of a pair of scissors is passed beneath the two lumbar nerves, that appear like white threads on each side of the vertebral column; the two or three lower vertebræ are removed, and thus the lumbar nerves are laid bare; they thus form the only link, which now connects the lower limbs with the superior vertebræ. If now the frog is suspended to an insulated conducting wire, by means of its nerves, and that, by touching the lower limbs with another conductor, a slight discharge or a feeble electric current is made to pass from the nerves to the muscles, the limbs of the frog are seen to undergo a sudden and extremely sharp contraction. The experiment may, in like manner, be made by placing the legs of the frog each in a separate glass, filled with water (*fig.* 257.); and by plunging into one of the glasses the zinc, and

into the other the copper of a small pair, the frog immediately undergoes a contraction of so great violence, that it is com-

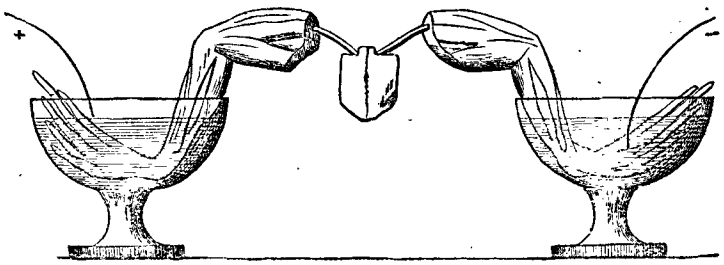


Fig. 257.

monly thrown from one glass into the other, or even from both glasses altogether. It is not necessary in order to obtain the contraction, to place the nerves and muscles in the circuit; it is merely necessary to cause the current to pass in a part, even a very short part of the nerves, for the muscles to contract; moreover, every existing action, exercised upon the nerve, produces an effect of the same kind.

But it is not upon the frog alone that the physiological action of the current has been studied. Galvani himself, and Aldini, nearly sixty years ago, produced contractions upon the head of an ox, recently killed, by introducing into one of its ears a wire in communication with one of the poles of the pile, and into the nostrils a wire in communication with the other pole. The eyes were immediately seen to open, the ears to shake, the tongue to move, and the nostrils to dilate; similar results were obtained upon divers animals. More recently, in 1818, Dr. Ure, on having endeavoured to to subject the body of a man who had been hanged, immediately after the execution, to the action of the current of a pile of 270 pairs of copper and zinc, of sixteen square inches of surface, and charged with water slightly acidulated with sulphuric and nitric acids, obtained some remarkable results. One of the electrodes of the pile, by means of an incision, was placed in contact with the spinal marrow, whilst the other was applied to the sciatic nerve, which had also been laid bare; immediately all the limbs of the body were agitated

by convulsive movements; on making the second conductor move from the hip to the heel, the knee having been previously bent, the leg was thrown out with such violence that it very nearly overthrew one of the assistants, who endeavoured in vain to prevent the extension. Other experiments made upon different parts of the body, produced contractions more or less violent in different organs, and especially in the diaphragm, to which they succeeded in giving a momentary movement, analogous to that which it possessed during life, thus bringing about a species of powerful and laboured respiration.

Humboldt who, from the origin of Galvani's discovery, had occupied himself upon this subject with much care, after various researches made upon animals, and to which we shall return, was desirous of studying the physiological action of electricity upon himself. Having applied blisters to each of the deltoid muscles, he placed upon one of his wounds a plate of silver and upon the other a plate of zinc, and, connecting the two plates by a wire, he established a pair, the current of which contracted alternately the muscles of the shoulder and of the neck, with a sensation of powerful smarting immediately that the bladder, formed by the blister, was open.

In order to experience the effect of the current upon one's own body, we have merely to plunge each of the hands into a vessel filled with salt water, communicating, one with the positive, the other with the negative pole, of a pile of some thirty pairs feebly charged; we immediately experience a shock which extends to the wrist or to the elbow, according to the intensity of the discharge. When the current passes for a certain time, and we hold in each hand a moistened metal cylinder sufficiently large to fill it entirely, we suffer a disagreeable sensation, analogous to trembling. If several persons take hold of each other's hands, the shock is experienced by all at the same time in a sensible manner, especially if the number of persons is not very considerable. The human body is not in effect a very good conductor. This is proved by the very exact experiments made by

Lenz with one of Nobili's multiplying galvanometers, by means of the inductive current of a Clark's machine, of which the following are the details.

The resistance is first determined of the entire circuit, composed of the induced wire, of the wire of the multiplier, and of the wires that are used for putting the multiplier in the circuit; and it is taken for unity: then an individual is interposed in the circuit, by causing him to plunge one or several fingers of each hand into two vessels, filled with a conducting liquid, which are themselves placed in communication with the extremities of the induced wire. The force of the current is alternately measured with and without the interposition of the human body, and a very exact mean is thus obtained of the effect of resistance, produced by this interposition. Thus, on employing for a conducting liquid, water acidulated with $\frac{1}{100}$ of sulphuric acid, it is found that the resistance, produced by the body of a man forty-three years of age, is thirty-four times the resistance taken for unity, when he plunges only one finger in each vessel, and only six times when he plunges the entire hand. The resistance is the more feeble, in proportion as the liquid is more acid, and consequently a better conductor; we, therefore, see by this, that the resistance exists chiefly in the passage of the current from the liquid into the body, and reciprocally; and that its cause consequently is in the epidermis. In effect, the immersed hand having accidentally received in one experiment a slight scratch, the resistance fell from 6·06 to 4·81, although the circumstances were in other respects perfectly the same.* Mercury, substituted for acidulated water, increases instead of diminishes the resistance, probably because it does not moisten the skin like the acid solution.

Resistance varies a little with the individuals submitted to experiment; it is in general much more considerable with

* No one who has occasionally handled voltaic piles, is ignorant how much the smallest scratch on a part of the hand, when it happens to come into contact with one of the electrodes, facilitates the production of the disagreeable sensation, arising from the passage of the current in the limbs.

children or with young persons than with more aged people. It is probable that this is due to differences in the surface of the fingers immersed; since the resistances differ less, when it is the entire hand, that is plunged, than when it is only one or two fingers. It would also seem that the right hand presents more resistance than the left hand, which may be due to the greater use that is made of it.

In order to compare the numerous results, that he has obtained with a known resistance, Lenz endeavoured, by the processes described*, to reduce the resistance of his circuit, not including the interposed human body, to that of a copper wire ·039 in. in thickness; and he found that it was equivalent to a length of this wire of 43,823 ft., which makes the mean of the resistances presented by the different individuals, to the number of six, submitted to experiment, equivalent to 300,203 ft. M. Pouillet had found this resistance equal to that of a copper wire, still of ·039 in. in diameter, but of 174,240 ft. in length, which makes a resistance of about one-half less; it is true that the hands were moistened and plunged into mercury, into which abutted the conducting wires of the current, which explains why the resistance was less considerable; but the same philosopher has observed that, if the current passes from one finger to another of the same hand, the fingers being moistened and plunged into mercury as far as the half or the third of the first joint, it is weakened seven times more, namely, as much as if it had traversed 1,219,680 ft. of copper wire. M. Pouillet, in these experiments, made use of a pile of twelve pairs of Wollaston's, and of a multiplier of 240 times, furnished with a very sensible magnetised needle.

More recently M. Masson has studied the physiological effect of discontinuous currents; he made use of a toothed-wheel to render the currents discontinuous, which traversed a long helix, in the interior of which was introduced a cylinder of soft iron, in order to render them more intense. He has remarked that, on placing a certain interval between each

* Vol. II. p. 80.

shock, shocks are felt that can be with difficulty endured; on increasing the velocity of the wheel, a time arrives when the muscles suffer an involuntary contraction, we can no longer relinquish the handles, that are held in the hands for transmitting the current through the body; the pain becomes insupportable, the arms writhe of themselves; and on increasing the intensity of the pile, the pain becomes so great that we faint away, unless the experiment be immediately terminated. On turning more rapidly, the pain diminishes, the contractions are less powerful, there remains only a numbness, which, with a certain velocity, itself finally disappears. This limit is not the same for all individuals; it varies in like manner with the intensity of the current. M. Masson, on applying a greater or less rapid succession of these electric shocks to very healthy cats, very promptly caused their death, which was accompanied by a stiffness of the limbs, similar to what the animal would have manifested, a fortnight after a natural death.

We shall return to the effects, observed by M. Masson, and in particular upon a property, which he has found to appertain to the induced current, that of only affecting the points of the body touched by the electrodes, when we are occupied with the applications of electricity as a curative means. We shall defer also to this part of our work many important details on the specific action of dynamic electricity upon the nervous and muscular system, as well as the description of various apparatus, contrived for producing currents intended for physiological applications, such as Neef's stunning wheel, of which they are only modifications; nor shall we pause to describe here the numerous researches of various physiologists upon the speciality of electric action, in regard to its physiological functions, because the results have been contested, and because, further, it is not until we have completed the theoretical study of electricity, and in particular of animal electricity, that we shall be able to discern in what this speciality may consist. We shall confine ourselves to calling to mind that Ritter had thought that the electricity of the positive pole increases the vital forces, whilst that of the ne-

gative diminishes them; that the former swells the parts of the body which it touches, and fortifies the pulse of the hand, whilst the latter reduces it. He had also thought he saw a different influence of the two poles upon vision, and upon the senses of taste and smell. All these effects, and many others besides, were evidently due either to the chemical or the colorific action of dynamic electricity, and not to a static action of the electricity of each pole. Wassali, Julio, Rossi, and Fowler, at the end of a great number of experiments upon the bodies of criminals after their execution, thought they found a specific action of electricity upon the heart and upon other muscles, such as those of the stomach and the intestines. Volta and Aldini had constantly denied the existence of this kind of action. Finally, Dr. Wilson Philipp, on making upon rabbits the section of the nerves of the eighth pair, had thought he might substitute an electric current for the action of these nerves upon digestion. Others had gone further, advancing that nervous influence is only an action, analogous to that of electricity. They had even attempted to substitute for this influence in secretions an electric current, acting directly upon the secreting organs. But all these results presented merely a false resemblance to those, which are brought about by the vital force, transmitted by the intervention of the nerves, as has been proved by a more deep and more detailed examination. We shall leave aside, therefore, all these researches, in order to study in a more precise and more scientific manner, with the different philosophers, who have been engaged with it, the real action of the electric current upon the different parts of the body of animals, of the frog in particular, confining ourselves to stating the positive facts, that multiplied experiments have placed beyond all kind of doubt. However, this study itself can be complete only when, entering in our Sixth Part upon physiological action, considered as a source of electricity, we may be able to estimate the share of influence, in the phenomena that are brought about by the application of an exterior and artificial electricity, that is exercised by the natural electricity, which

the animal possesses, and which is connected with its physiological functions.

Fundamental Analysis of the Action of the Electric Current upon Animals.

The action of the electric current upon animals is manifested distinctively only under two forms: pain, the perception of which can be indicated distinctively by man alone; muscular contraction, which is sensible with all animals, by the movements that are its result, and which may even be manifested for a longer or shorter time after they have ceased to live. It consists of a shortening of the fibres, of which the muscle is composed, attended by an increase in their diameter, without any change taking place in the volume of the muscle itself. M. Matteucci demonstrated this, by placing a torpedo and a frog, prepared after Galvani's method, in a vessel filled with water and closed with a cork, traversed by a narrow tube, in which the liquid rises; an electric current is directed into the vessel by means of two insulated wires; and although the torpedo and the frog suffer powerful contractions, the level of this liquid column in the tube is not seen to undergo the least change.

We shall not dwell here on the details relative to the structure of the muscle, and on the hypotheses that have been formed of the manner, in which its construction is brought about; we shall confine ourselves to adding, that the cause, which determines it in the animal in the normal state, is the influence that is transmitted by the nerves, which is designated by the name of nervous force.* The collection of these nerves constitutes the cerebro-spinal nervous system, which is principally composed of an infinite number of ramifications, disseminated in the body of the animal, uniting in one central mass, which forms the brain and the spinal

* We designedly exclude the term *nervous fluid*, which is sometimes employed, because it rests upon an hypothesis, with respect to the nature of nervous force, which nothing justifies.

marrow.* If we cut one of these ramifications in a living animal, and touch it with a red-hot iron, or a piece of potash, or if we wound or pull in any manner the portion of this nerve, that remains in communication with the cerebro-spinal axis, the animal gives signs of pain. On producing these same irritations below the section, the signs of pain are not manifested; and we merely perceive contractions in the muscles, among which the irritated nerve ramifies. When these excitations are administered to the intact nerve, pain and contraction are simultaneously produced. Instead of cutting the nerve, we may tie it, which produces the same effect as the cutting; but, if we tie it in two points, and irritate it in the portion comprised between the two ligatures, neither pain nor excitation is produced. The nerve, therefore, has the office of transmitting the action of the stimulant applied to it, either to the brain, when it produces a sensation, or to the muscles, when it brings about a contraction. The modern discoveries of physiologists have demonstrated that, among the nerves, there are a certain number, which, on being excited, produce, some, muscular contraction alone, others pain alone. We may add, that a bundle of nerves is composed of a great number of filaments, all capable of transmitting separately the action by which they are excited without the filaments, with which the one excited is in contact, taking part in it. With regard to the actual nature of the nerves, we will confine ourselves to remarking, that it is a fatty matter contained in small cylindrical canals, of a firmer consistence, and which are termed neurilœma, without entering for the present into further details on their physical and chemical constitution, which have formed the subject of the researches of a great number of physiologists.

The causes capable of developing in nerves the nervous force, which, by propagating itself to the muscles, produces

* Besides the cerebro-spinal nervous system, there exists a second, the ganglion nervous system, composed of ramifications, distributed principally in the apparatus of organic life, which, notwithstanding its numerous relations to the former, yet gives rise to neither motions nor sensations, when it is irritated. We shall not trouble ourselves with this system, in the researches, that form the subject of the present paragraph.

in them contraction, are first and above all the will, then mechanical actions, chemical actions, heat, and finally electricity; but electricity in its mode of action, differs from the other exterior agents, by characteristics that are peculiar to itself, and which give it in this respect a much greater relative importance, by approximating its effect to that of the agent, which the will calls into action. The following are the principal characteristics, whose existence we are about to establish: the electric current is the only irritant that is able to excite sometimes contraction, at other times sensation, according to the direction in which it traverses a nerve; the electric current does not produce any of the phenomena, which result from the excitability of the nerve, when it traverses it perpendicularly to its length; it brings about neither contraction nor sensation, when its action upon the nerve is prolonged; it alone is able to modify the excitability of the nerve, even to destroy it, if it circulates in a certain direction; and to preserve or even to increase it, if guided in the converse direction; finally, it alone, among irritating agents, is able to revive for a long time the excitability of nerves, when it is very much enfeebled in respect to other stimulants.

We have already related, in the preceding paragraph, Galvani's fundamental experiment, and his manner of preparing the frog. Volta and Fowler had remarked, on repeating and varying this experiment, that the same contractions as the frog suffers at the moment when the current is established, are renewed at the moment when this current ceases to traverse it. This fact studied successively by Valli, Rumford, and Pfaff, had been attributed by Volta to a species of rebounding, which is experienced by the current at the moment of the breaking of the circuit, by the instantaneous obstacle that it encounters; as would be the case with a fluid, which, while travelling in a canal, would recede and move in an opposite direction, should it be suddenly arrested. Marianini, who has carefully studied this phenomenon, has not succeeded in proving the existence of Volta's hypothetical counter-current, when employing either a galvanometer or the sensation exercised by the current upon

the tongue; he has therefore conceived that, on removing the communications by which the current is transmitted from a pile, no opposed current is originated. It is therefore to the single fact, that it ceases to be traversed by the current, that the frog owes the second contraction, which it suffers; and the proof is, that for producing it we have merely to connect by an arc of metal the two conductors which establish communication between the two poles of the pile and the frog. Its contraction is brought about, on thus deriving, by a better conductor, the current that continues to traverse in a circuit of which the animal, it is true, no longer forms a part. However, Marianini has shown, that the contraction which takes place at the moment of the irruption of the current, and that which takes place at the moment of its cessation, have not the same intensity; at least, when the frog has lost its excitability, one or other of them is the more powerful, according to the direction in which the current is travelling, in respect to the nervous ramifications. In order well to appreciate this difference, a frog must be prepared so that the thighs are attached to the trunk by the lumbar nerves alone (*fig.* 258.). The trunk is placed in a cup filled

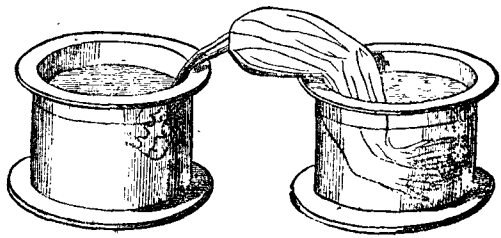


Fig. 258.

with water, which communicates with one of the poles, and the two thighs in another cup, in communication with the other pole. If the positive pole is in the cup in which the trunk is placed, and the negative in that in which the thighs are, the frog contracts every time the circuit is closed, and not when it is opened; on changing the poles, the effects are converse. The result proves that, in order for contraction to take place, when the circuit is closed, it is necessary

for the current to travel in the direction of the ramification of the nerves; and that, in order to its taking place, when it is opened, it is necessary for the current to travel in a contrary direction to the ramification. We shall term *direct* current the one that travels in the former direction, and *inverse* the one that travels in the latter.

The same phenomenon is manifested when the experiment is made with a frog prepared as above, but arranged so that one of the thighs plunges in one of the glasses, and the other in the other (*fig.* 259.). The frog, as we know, leaps out

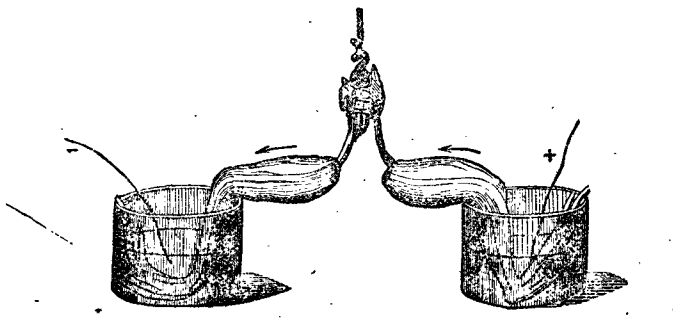


Fig. 259.

of the glasses when one of the poles of the pile is plunged into each; but if we forcibly retain it in its place, we at first perceive contractions in both legs, as well on opening as on closing the circuit. By continuing to operate, a time arrives when, the excitability of the animal being diminished, a single limb contracts, when the circuit is closed; it is the one in which the current is direct; and, on the contrary, when it is interrupted, the contraction takes place in the other limb, namely, in that which is traversed by the inverse current.

This important fact, well analysed and established by Marianini, had been in part recognised by Volta, by Lehot and by Bellinghieri; who had not, however, remarked the essential point, which M. Marianini was the first to point out, that in the case of the inverse current there is contraction, when the current is interrupted, even when there is none when it is established. We may add, that with two frogs placed in the

circuit, one after the other, so that their two trunks are plunged into the same vessel, the thighs of the one communicating with the positive pole, and those of the other with the negative, the one that is traversed by the direct current, and not the other that is traversed by the inverse current, is seen to tremble at the establishment of the circuit; whilst at the rupture of the circuit it is the latter and not the former that trembles.

M. Marianini has further observed that, when electricity acts immediately upon the muscles, contractions take place, only at the instant, when the circuit is closed, whatever be, in other respects, the direction of the current; whereas he is led to distinguish these latter, which he terms *idiopathic*, from those which are derived from the action, exercised by the electric current upon the nerves, that preside over the movement of the same muscles, and which he terms *sympathetic*. We have just seen, that they take place only at the establishment of the circuit and not at its rupture, if the current is direct; and only at its rupture, and not at its establishment, if it is the reverse. But in the two cases, in which there is no contraction, might there not have been a sensation, at least if the animal is living? Marianini conceived he had established this, on operating on a frog, whose posterior limbs remained attached to the body only by the two crural nerves, and by placing these limbs united together in communication with one of the poles, whilst one of the anterior legs, the right, communicated with the other pole. If the current entered into the nerves in the direction of their ramification, the frog agitated the inferior extremities, at the moment when the circuit was closed, and at the moment when it was interrupted, it uttered a prolonged cry, with the full force of its lungs, and at the same time raised itself with contortions upon its anterior limbs, without agitating the inferior. If the current penetrated the nerves in the direction contrary to their ramification, it was when the communications were established that the frog uttered its cry, accompanied with contortions; and that it repeated it, if the circuit was left closed for some time; and, when it was interrupted,

the posterior extremities were agitated, and the animal ceased to cry and to present contortions.

M. Marianini quotes a curious experiment in support of the distinction, that he has established between idiopathic and sympathetic contractions, and of the difference of effects of the current in the case in which, when circulating in the nerves, it traverses them in the direction of their ramification or in the contrary direction. It consists simply in placing the right hand in communication with one of the poles of the pile, the positive for example, and the left with the other, the negative; every time the circuit is closed, a contraction is felt in both arms, but stronger in the left than in the right; if the current is made to pass in the contrary direction, it is the right that suffers the more powerful contraction. An analogous effect is obtained, on making one of the poles communicate with the arm and the other with the foot. The contraction is more powerful in the limb in which the current circulates in the direction of the ramification of the nerves; because it is at the same time sympathetic and idiopathic, than in the other limb, in which it is only idiopathic. It would appear that, among individuals sensible to the effects of electricity, the shock is, in the latter case, accompanied by a peculiar sensation, which does not take place in the former case, in which it is more violent.

M. Nobili, as the result of a very complete analysis of the phenomena, described by Marianini, succeeded in distinguishing five periods in the degree of irritability of the frog; the first, in which there is contraction with the direct and with the inverse current, whether the circuit is established, or opened; the second, in which there are no longer any contractions, when the inverse current is established; the third, when the contractions also cease with the rupture of the direct current; the fourth, when the contractions, due to the establishment of the direct current, alone remain; finally, the fifth, in which there are no longer contractions in any case. It is clear that it is always necessary to operate with the same voltaic arc, for all the limits would be thrown back, if the force of the current was more considerable. In

all these experiments, M. Nobili operated upon the nerve alone, by applying to the extremities of the insulated crural nerve the two ends of the voltaic arc, taking good care not to touch the muscle.

Whilst the current is circulating, there are no sensible contractions, which does not prove that there is not a certain effect produced upon the nerve by the current. Volta had already remarked that a frog, left for half an hour in the circuit of a pile, no longer contracts under the action of the same current; whilst it suffers a very lively agitation, if it is exposed to the action of an inverse current. We see plainly by this, that the continuous action of a current does not disorganise the nerve, but that it alters it, however, to a certain degree, by placing it in a different state from its natural state; if the action has endured a short time, the nerve has not become habituated to its new state, so that, when the current ceases, it immediately recovers its natural condition, and a new invasion of the current brings about the same effects. But when, by the duration of the action, it is accustomed to its new state, it may remain in it for a longer or a shorter time, even when the cause that has produced upon it this alteration no longer exists. Thus if, after having suspended the current for a moment, it is made to act anew, it produces no effect, because it finds the nerve still in the condition which it tends to produce in it. It is no longer the same, when the direction of the current is changed; the more the nerve has become accustomed to the effects of this first current, the less easily will it support the action of the second. Experiment does not teach in what the modifications consist, which the nerve suffers under the action of the direct and inverse currents; it only points out to us that one of the modifications is very different from the other; M. Nobili calls one *direct alteration*, it is that, which is produced by the direct current; and the other, which is produced by the inverse current, *inverse alteration*.

The animal may therefore be found in three states; the natural state, before the current passes, the state of direct alteration, and the state of inverse alteration. In order that

there shall be a shock, two conditions are necessary; the first, that the nerve shall pass from one state to the other; the second, that this state shall take place rapidly. M. Marianini had, in fact, remarked, that if the passage from one state to the other, namely, the establishment, or the rupture of the current takes place slowly and gradually, the shock is null, or very feeble. The transition from one state to the other brings about a shock; and, as there are four possible transitions, there are four shocks, of which two are comparatively *more feeble* in comparison with two other *stronger* ones, which endure for a longer time. The following is the actual order, in which they disappear: *the more feeble*, which belongs to the inverse current, at the moment when it is established; *the less feeble*, which is due to the direct current at the moment when it is interrupted; *the less powerful*, which is due to the inverse current at the moment when it is interrupted; the *more powerful*, which is due to the direct current, at the moment when it is established.

In the first period of great excitability, the differences between the four contractions are too small to be able to be detected. In order to explain what takes place in the others, M. Nobili supposes that the nerve possesses a structure, which renders it fit for propagating certain movements in the direction of its ramifications; whence it follows that the direct current, acting upon the nerve in the direction of its fibres, produces in it a contraction, whilst the inverse current, acting in a contrary direction, does not produce any, or only produces one, when the nerve being very irritable, is capable, like an elastic cord, of propagating the motion that it receives in two directions, but with more intensity, however, in that direction, according to which the force is acting. If the circulation of the direct current tends to alter the structure of the nerve in the direction of its fibres, and in that of its ramifications, that of the inverse current tends to alter it in the opposite direction, which causes that, for the same intensity of current, the former alteration will give to the nerve a less forced condition than the latter. It will follow from this, that the interruption of the current ought to produce a less

violent shock, in the case of the direct current, than in the case of the inverse current, which constrains the nerve into a state further from that which is natural to it.

Such, in brief, are M. Nobili's ideas, which, even though they cannot be admitted under the too explicit form, that he has given to them, are not the less founded, as we shall see, upon the truth. We may further add, that the law of contractions, such as he has formularised it, varies with the force of the current, and that, in particular, powerful currents are proportionately more active, when the circuit is interrupted, than when it is closed; and that the reverse is the case for feeble currents; which is due to the greater alteration that is produced by the former in the nerves. Furthermore, M. Nobili has recognised that his law of contractions is not modified, by the presence of the muscles in the circuit; and, in fact, the same effects are obtained, by placing the frog in such a manner, that the current passes from the crural nerve into its lower limbs, as when it passes in a portion of the nerve only. But, it is no longer the same if the current traverses the muscles alone: the shock then takes place only when the circuit is closed, and we no longer observe those which were produced, when it was interrupted, seeing that they were due to the alteration of the nerve, that was traversed by the current.

We should in this place revert for a moment, to one of the phenomena, that we have described in passing, but which merits a deeper examination; it is that, to which philosophers have agreed to give the name of *voltaic alternatives*, on account of Volta, who was the first to observe it. We have seen that this celebrated philosopher, having placed astride, on two glasses of water, placed in the circuit of the pile (*fig.* 257.), a frog recently killed and prepared, according to Galvani's method, remarked that, if the circuit had remained constantly closed for half an hour, the legs of the animal no longer contracted, when the circuit was opened and when it was closed. But, on making a current pass in a direction, contrary to the former, the circuit could be neither opened nor closed, without the contractions being renewed each time. If the current was again made to act for half an hour, the

muscles lost in this second state all their contractability, but they regained it, upon recovering their former position. On thus bringing about changes, from half-hour to half-hour, and even more frequently, we are able for an entire day and even longer, to annihilate or to revive at pleasure the natural excitability of the muscles of the animal.

The weakening, that is suffered in the frog's property of contracting is the more considerable, as the current is more powerful; but although in general it may contract anew, under the action of a more intense current, yet its sensibility is found to be enfeebled. M. Marianini has very well demonstrated this, by means of two perfectly similar frogs, prepared in the same manner, and at the same time, of which one had been left at rest, whilst the other had been subjected to the action of the current of forty pairs. The operation had lasted for half an hour; at the end of a second half-hour the former frog was still sensible to the current of a single pair, almost as much as at the commencement, whilst the latter remained motionless under the action of two pairs. If the animal is living, the vital force repairs the damage done to the organs of motion by the current. M. Marianini satisfied himself of this, by passing the electric current of sixty pairs, from one of the legs of the living frog to the other, by means of two bands of lead. It was merely necessary for it to obtain some relaxation, when its muscular contractions have been enfeebled, under the action of the current, in order that, regaining its primitive strength, its contractions may recover their vigour, without its being necessary to subject it to the action of a contrary current. This repairing principle does not entirely cease with life; it subsists, at least in part, for some time after death; however, it is in the living animal, that it acts with the greatest energy.

This weakening of the excitability of the nerves is principally manifested in the portion that is traversed by the current, as Matteucci proved on applying the current to a portion of the nerve, more distant from the brain than was that upon which he had operated for a sufficient time to cause the contractions to cease; the contractions are immediately

seen to reappear, as also the same phenomena as before. On following out these experiments, so as to act upon portions of the nerve, still more distant from the brain, the same effects are still obtained. If the animal is living, we find, on the other hand, that the signs of pain which it manifests, when a current traverses its nerves, are revived, if we act upon parts more and more near to the brain, in proportion as its vivacity diminishes by the prolonged passage of the current. In both cases equally, it is always the excitability of the nerves that is enfeebled by this passage. This experiment is important, in that it shows that the phenomena of voltaic alternatives cannot be attributed, as was done by Marianini, to the fact that a part of the electricity which enters into the organs of motion, remains there for some time, and accumulates more and more, until, by a tendency to flow back, it opposes the current, that arrives at the same organs, so that the action of this current becomes null, or excites feebler contractions, than at the commencement of the experiment. Besides, there is nothing that demonstrates this arrest of electricity, which would be, as it were, a species of polarisation of the extreme parts of the portions of the frog, placed in the circuit. We therefore see, as Nobili has so clearly explained, that the electric current brings about in the portion of the nerve that it traverses, an alteration, which is stronger in proportion as its passage is more prolonged; an alteration, that renders the nerve incapable of transmitting the action of a current, acting in the same direction, and which is only able to disappear by the passage of a current, guided in a contrary direction, or by a rest of some duration, until, by repeated actions, the nerve has lost all excitability. What is the nature of this alteration? It is probable that it is connected with the state, into which the transmission of the current reduces the nerve; a state which, by analogy with what takes place in all other cases, must be a polarisation of the molecules, alternating with molecular discharges. We conceive that so long as the nerve has sufficient vitality, it reacts as soon as the current ceases, in order that the molecules may recover their natural position;

but a moment may arrive when this reaction, no longer taking place, a current guided in the opposite direction, is necessary, in order to bring it about.

An important fact, observed by Matteucci, comes to the support of our manner of regarding it. This learned philosopher has observed that the tying of a nerve, for example, the crural nerve of a rabbit, produces the same effect, as would have been brought about by the prolonged passage of the current in the part of the nerve, comprised between the two ligatures. Thus, if the current is made to pass below the ligature, the contractions of the leg are observed; and if it is made to pass above, there is no longer any contraction, but there are signs of pain, because there is communication with the brain, without an intermediate ligature. It is necessary, in order to perform this experiment well, to take care to insulate the nerve from the moist parts, by which it is surrounded, and properly to tighten the ligature; without this precaution, a portion of the current is able to pass above or below the ligature, and to interfere with the results. It must be remarked, that the ligature does not intercept the current, but weakens its effects; so that, if one of the poles is placed above and the other below the ligature, the phenomena are the same, as if there was no ligature, but only more feeble. For all these experiments, the best plan is to employ the frog, prepared in the usual manner, and to suspend it by its nerve (*fig.* 255.).

One of the characteristics, whereby the most marked difference is established, between the physiological action of electricity and that of other agents, is the connection that exists between the direction of the propagation of the current and the direction of the nerves and of their ramifications. We have already even remarked that the electric current does not produce any of the effects due to the excitability of the nerves, when it is transmitted transversely to this nerve. The following is the method whereby Matteucci has demonstrated this important point. Two frogs' legs are prepared and separated (*fig.* 260.), so that their nervous filaments cross each other at right angles; one of the nerves is cut, so that the

two extremities of the section made are at a distance of about $\frac{3}{4}$ in. from each other, and only $\frac{5}{8}$ in. from the nerve of the other leg, which passes across the section; a drop of distilled water establishes a communication between the two sections of the cut nerve. The points *a* and *b* of the cut nerve are then touched with the poles of a pile composed of a very great number of pairs; the current traverses, not only the water, but the interposed nerve; nevertheless, the leg, to which this nerve appertains, suffers no effect, whilst the other suffers violent contractions. However, if the pile is still more powerful, we end by perceiving some contractions in the leg, whose nerve is traversed transversely by the current; but they are much more feeble than in the other leg.

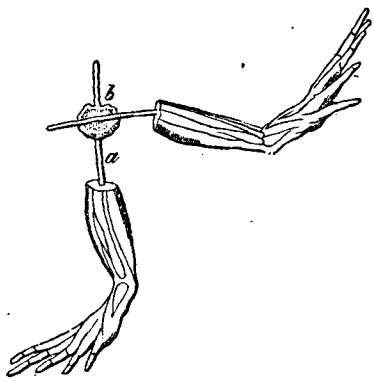


Fig. 260.

Among the multiplied researches of which the physiological action of the current has been the subject, we shall confine ourselves to pointing out in this place a few, either on account of their importance, or because we shall not have occasion to return to them, as to others, when engaged with animal electricity.

One of those, which we have in view, is the determination, that M. Matteucci has endeavoured to make, of the relation, that exists between the quantity of electricity transmitted and the contraction excited by this quantity of electricity in a nerve of an animal, either living or killed as recently as possible. The apparatus that he employed consists principally of a solid brass rod, A B, *fig.* 261., fixed upon a wooden base, and in which there slide at right angles two pieces of metal C and D, which can be fixed in different points by binding-screws. The piece C carries the clip E, into which is introduced and pressed with three

screws the pieces of the spinal marrow of the prepared frog. The other piece F, in the form of a fork, is arranged so as to

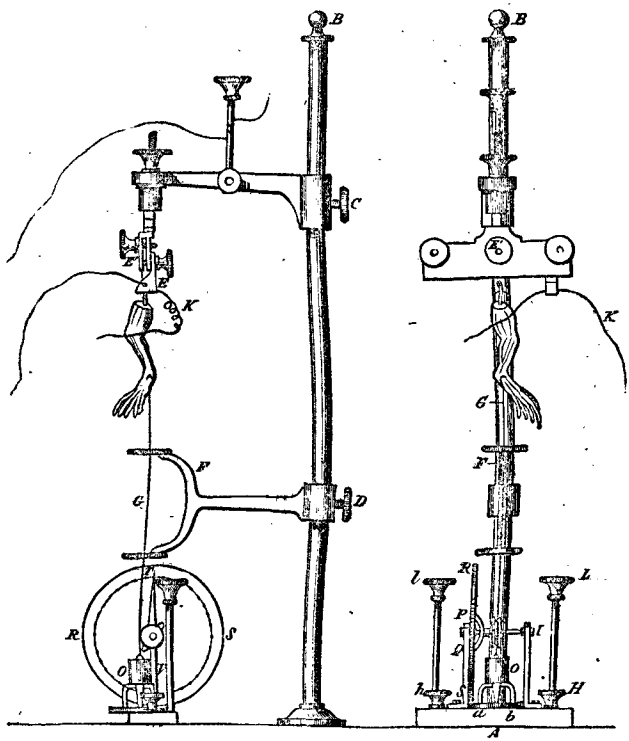


Fig. 261.

have two holes at its two extremities, into which is introduced and by which is regulated a very fine wire. This wire G is terminated at the one end by a hook, which is fixed in the paw of the frog; at the other it is attached to a silk thread, which is wound over this little pulley I. On this same pulley is coiled, in the contrary direction, another silk thread, to which is attached a little leaden weight O. The axis of the pulley carries a species of double index, P Q, which has the form of a semi-circle. The axis is fixed upon two pivots, which may be brought to greater or less distances from each other. One of these pivots is at the centre of the circle R S,

which carries a division. In this same pivot is introduced a long and very light ivory needle T V, and which turns with the least possible friction. It is not difficult to conceive the use of this ivory index. In effect, if this index is carried into contact with the other, which has the form of a semicircle P Q, and which is fixed upon the axis of the pulley, it will occur that, on turning this pulley, the ivory index will be also pushed, and it will stop at the point to which it has arrived, even when the pulley shall have been brought back to its position by the little weight. It is necessary to mention that, without this ivory index, it would have been impossible to judge of the extent of the movement of the pulley, produced by the contraction, on account of its very short duration. The weight employed was $9\frac{1}{4}$ grains. It is sufficient for the limb to return to its position, the contraction having ceased; a heavier weight would have strained the nerve too much. The following is the method by which the current is made to pass. It is always a half-frog, whose muscles and pelvis bone have been removed, that is the subject of experiment. The half-frog is thus reduced to a piece of spinal marrow, which is pressed in the clip E, to the nervous filament, and to the thigh and leg only, the paws having been cut away. The wire hook G is introduced between the bone and the tendon Achilles. Finally, a gilt steel needle is inserted into the muscles of the thigh, as near as possible to the insertion of the nerve; to this needle is soldered a copper wire K, very thin and covered with silk, which is fixed to a piece of ivory E. It is clear that, in order to cause the current to traverse the nerve, we have merely to touch with the poles of the pile the rod A B, in any point, and the wire K, that is soldered to the steel needle.

Now, in order to operate, it is necessary to pass an electric current, or a certain discharge of the Leyden jar, through a certain length of the nerve of the frog; the electro-physiological effect is the contraction of the limb, which, in a certain time, rises to a certain height. But the difficulty is, to cause quantities of electricity to pass, that shall be in given

relations to each other, so as to compare them with the corresponding electro-physiological effect. At first it is necessary to employ a very feeble current, so that the effects shall not be all at their maximum; the current of one pair, even reduced by its passage through water, is sufficient; then, in order to cause, sometimes the half, at other times the third or the fourth, of the electricity to pass in the same nerve, M. Matteucci interposed between the pincers and the thigh one, two, or three nerves, as similar as possible, both in respect to each other, as well as in respect to the nerve, that is the subject of the experiment; and admitting as approximately true that the half of the current passes in each of the nerves, when there are two, the third, when there are three, and so on, he was enabled to reduce, into the desired proportion, the current, that passes by the principal nerve.* The following is one of the numerous experiments, that M. Matteucci has made in this manner: —

Number of nerves.	Degrees of contraction.
1	26
2	14
3	8

Although, in general, the results differ very notably among themselves, which is inevitable in this class of experiments, M. Matteucci thought he was able to conclude from them that *the physiological effect is proportional to the intensity of the electric current.*

However, it is not probable that this class of action can be subjected to very precise laws; and a German philosopher, who has gone through great and important labours on this subject, M. Du Bois-Reymond, has thought he was able to establish the following fundamental law, as governing electric excitation; namely, that *the motor nerves are not excited by the absolute largeness of the density*†

* It is true that, on increasing the number of nerves, the total current must increase; but, as the nerves are very imperfect conductors, this increase is not considerable.

† M. Du Bois-Reymond, designates by the name of density of the current in

of the current, but by the variations that occur in the sum of this density from one instant to the other; the excitation, caused by these changes, being greater in proportion as they take place more rapidly, or as they are more considerable in a given time. Now, this law, established by numerous experiments, cannot be reconciled with that of M. Matteucci. We may, as M. Du Bois-Reymond has done, represent, in each case, these effects by two curves, in which the abscissæ represent the time, and the ordinates represent, in one of the curves, the density of the current in the nerve and in the other the value of the excitation; but these are merely very approximative results. A very curious case is that, in which the excitation is produced by a series of successive discharges, which follow each other very rapidly; for example, by means of an apparatus, like Masson's toothed-wheel, which interrupts and re-establishes the current in a very rapid manner. The effect of such a series of discharges is to produce a tetanic contraction of the muscles; as Volta was the first to observe, and as Nobili afterwards pointed out more in detail.* In experiments upon animal electricity, we are often called upon to bring about in this way tetanus in the limbs of an animal.

We shall not terminate what relates to the action of the electric current upon the nerves, without saying a few words upon the application, that has been made of it for the construction of a physiological galvanoscope. Although the magnetic galvanometer-multiplier has become, especially with the perfection that Du Bois-Reymond has introduced into its construction †, an instrument, eminently suited to the perception and to the measurement of currents, due to animal electricity, there are, nevertheless, cases, in which its employment is insufficient, and even presents inconveniences. In this case, we may advantageously employ the physiological

a section of the circuit, the quotient of the intensity of the current, divided by the size of the section of the conductor.

* It is an effect of this kind, that is experienced in Masson's experiment, of which we have spoken in the preceding paragraph.

† *Vide* Vol. I. p. 331.

Fig. 262.

galvanoscope, which Nobili was the first to use, employing the frog, prepared after the manner of Galvani (*fig.* 256.). Matteucci and Du Bois-Reymond have found that it was preferable, instead of employing, like Nobili, the entire frog, simply to detach a thigh furnished with its nerve, which may be placed in a varnished tube, in order well to insulate it (*fig.* 262.), so as to allow only the portion of the nerve to stand out which we desire to insert in the circuit, that is the subject of the experiment. It is in effect a matter of importance to be assured that neither the current proper of the thigh, nor any current other than that which is being studied, shall traverse this nerve. The contraction of the thigh indicates the passage of a current in the nerve; but only at the moment, when this passage commences and finishes, which prevents this galvanoscope from indicating whether the discharge is instantaneous or continuous.

Among other applications that have been made of the physiological galvanoscope, we shall only point out one, which is due to M. Du Bois-Reymond, and which consists in showing the development of dynamic electricity, that may take place by the induction, brought about by means of a magnet, or of a current in a circuit, that is not closed, such as a wire. We have merely to place a galvanoscopic frog at each of the extremities of this wire, in order to see them contract, as soon as the current or the inducing magnet is brought near, providing we at the same time touch it with the fingers, in order to determine the passage of the induced current. It is sufficient to touch merely one of the frogs, for the other also to contract, if they are sufficiently sensible. We can also obtain an effect upon the frog by touching with its nerve an imperfect conductor, such as a moist thread, which unites the two extremities of the open induced circuit; but, for this purpose, it is necessary that the frog be not insulated, and that its nerve touches the thread, near one of the ends

of the induced wire; and, if it is not very sensible, it suffers contractions only when the end near which the nerve is, is that by which the positive electricity arrives. A nerve may be substituted for the moist thread, so that contractions may be excited in the galvanoscopic frog simply by making an induced current pass through the portion of the nerve, that is above a ligature, which may give rise to errors in the study of animal electricity, if great attention is not paid to it.

This last species of action approximates closely in that which Matteucci has described under the name of induced contraction, with this difference, that, in this latter case, the nerve of the electroscopic frog is affected, not by an electric current, but by its contact with the nerve of another frog; an effect, that is due, as we shall see, to the electricity, which probably circulates in this nerve. Moreover, it is only when we shall have studied animal electricity considered itself as a source of electricity, that we shall be enabled to have more just and more complete notions of the physiological action of electricity in general, the effects of which are necessarily complicated with those that are due to the electricity proper of the animal.

In all that precedes we have been only occupied with the effects that result from the passage of dynamic electricity, either through the nerves alone, or through the nerves and muscles at the same time, when the discharge or the current traverse the animal in its entire length. It remains for us to say a few words upon the action of the current on isolated muscular fibre. This research is very difficult, because, even when we have removed from a muscle all the nervous filaments that are visible, it is a difficult matter for no trace of the nervous substance to remain; nevertheless, by taking all the necessary precautions, we are enabled to arrive at results that are tolerably exact. Thus, on causing the current of a pile of thirty or forty pairs to pass through the pectoral muscle of a pigeon, deprived as well as is possible of its nerves, we may show that the muscular fibres contract, when a circuit is closed, and when it is opened; and this, whatever be the direction of the current,

relatively to that of the fibres. These contractions cease during the passage of the current; but they reappear, although more feeble, when, after having interrupted the circuit, it is re-established; at least whenever the former passage has not been too prolonged; in which case, the contractions can no longer be produced.

The effects that we have been pointing out, can only be due to the direct action of the current upon the muscular fibre; for even though there should remain some nervous filaments in the muscle, since the nervous matter is much less conducteous, about four times less than muscular matter, it is essentially the latter, that is traversed by the electricity.* M. Matteucci, to whom we are indebted for these observations, has, moreover, proved directly that no part of the current passes through the small nervous filaments, when it traverses the muscle; for this purpose he takes the muscle of the leg of a rabbit, or of a dog, that has been dead a sufficiently long time for all muscular irritability to have disappeared; he then makes in this muscle an incision, and introduces into it the nerve of a very sensible galvanoscopic frog (*fig.* 262.), so that it may be well covered with the muscle. As soon as the contractions, that are manifested in the frog, at the first moment, have ceased, he causes the current of a pile of from twenty to thirty pairs to pass through the mass of the muscle, by applying the electrodes upon different points

* In order to determine the relative conductibility of nerves and muscles, M. Matteucci took from a rabbit recently killed, a sufficiently long piece of the sciatic nerve, a layer of the cerebral substance, and a piece of muscle, removed from the thigh. He reduced these substances to slices of the same thickness, as nearly as possible, and he placed them one after the other on an insulating plane; then he caused the current of a pile of twelve pairs to pass through this chain of animal substances. He then touched, with the platinum extremities of a sensible galvanometer, sometimes one, sometimes the other of the animal substances, the two wires being always held at the same distance; and he thus obtained deviations, produced by derived currents, drawn under the same circumstances, from the three substances mentioned. He also made the experiment in another manner, by causing the distance of the two platinum wires to vary, so as to obtain a derived current of the same intensity by operating upon the three substances. The derived current, in the former case, is the more powerful as the substance is a worse conductor; thus, it is more feeble with the muscle than with the nerve, and with the nerve than with the cerebral substance; whence it follows, that this substance conducts a little less well than the nerve, and the latter about four times less than the muscle.

of this mass; and although this energetic current traverses the muscle in all directions, the frog undergoes no contraction, nevertheless, its nerve is contained in this muscle, and forms almost one integrant part of it. Care must be taken to employ a muscle, whose irritability is extinguished; for without this, the frog suffers contractions, which are due to the phenomena of induced contraction, with which we shall be occupied in the sequel.

Returning to the contraction excited directly upon the muscles, we will further remark that, when it takes place by the effect of the discharge of a Leyden jar, it occasions in the muscle a persistent deadly stiffness, accompanied by a shortening; this is an effect similar to that, which Nobili, Masson, and Matteucci have successively obtained by causing a discontinuous current to pass through the nerve of an animal, which brings about a veritable tetanus; a tetanus that may be made to cease, either by the passage of a current the inverse of that, by which it has been produced, or by dividing the nerve, that communicates with the tetanised limb.

We shall here terminate what we have to say for the present on the physiological effects of electricity; we shall return to many of the points that we have omitted; such in particular as the influence upon the effects of electricity, of poisons, and of narcotics previously administered to the animals, as well as upon the analysis of the sensations that are produced in men by the passage of dynamic electricity in different parts of their organs. These subjects, as well as other analogous ones, will naturally find their place in the chapter of this Treatise, which will be devoted to the Therapeutic Applications of Electricity; and they can then be treated in a much more complete manner, because we shall have studied, what we have not yet done, the phenomena relative to the production of electricity by physiological actions, which are designated under the name of *animal electricity*.*

* *List of the principal works relating to the subjects treated upon in this Chapter.*

Davy.—Electro-chemical decomposition of organic substances. *Ann. de Chim.* t. lxiii. pp. 223, 255, and 261.

Gay-Lussac.—Effects of electricity upon the fermentation of must. *Ann. de Chim.* t. lxxvi. p. 257.

Becquerel.—Application of electro-chemical forces to vegetable physiology. *Ann. de Chim. et de Phys.* t. lii. p. 57.

Matteucci.—Influence of electricity upon germination. *Ann. de Chim. et de Phys.* (new series) t. ii. p. 403.—Electro-physiological researches. *Ann. de Chim. et de Phys.* (new series) t. ii. p. 403.; t. xix. p. 52.; t. xxiii. p. 241. *Phil. Trans. of the Royal Soc. London*, 1846-7-9 and 1850. *Treatise on the Electro-physiological Phenomena of Animals.* Paris, 1844, in 8vo. with plates.

Dutrochet and Becquerel.—Influence of electricity upon the circulation of the chara. *Bibl. Univ.* (new series.) t. xii. p 394. (1837.)

Lassaigne.—Precipitation of albumen at the positive pole. *Ann. de Chim. et de Phys.* t. xx. p. 97.

Galvani.—Resumé of his electro-physiological works. *Ann. de Chim. et de Phys.* t. xxv. p. 58.

Humboldt.—Irritation caused by metals upon animals. *Ann. de Chim.* t. xxii. p. 51.

Ure.—Electric experiments upon a corpse. *Ann. de Chim. et de Phys.* t. xiv. p. 337.

Lenz.—Electric conductibility of the human body. *Arch. de l'Elect.* t. iii. p. 534.

Pouillet.—Idem. *Compte rendu de l'Académie des Sciences*, t. iv. p. 791.

Masson.—Physiological effects of discontinuous currents. *Ann. de Chim. et de Phys.* t. lxvi. p. 5.

Philipps.—Action of the current replacing that of the nerves. *Ann. de Chim. et de Phys.* t. xxii. p. 216.

Volta.—Animal electricity. *Ann. de Chim.* t. xxiii. p. 276. and t. xxix. p. 91.

Marianini.—Various memoirs relative to the physiological action of the current. *Ann. de Chim. et de Phys.* t. xl. p. 225.; t. xliii. p. 320.; t. lvi. p. 387.

Nobili.—Idem. *Ann. de Chim. et de Phys.* t. xxxviii. p. 225.; t. xliv. p. 60.

Du Bois-Reymond.—Idem. *Ann. der Physik. passim. Untersuchungen über thierische Electricitat.* Berlin, 1848, t. i.

PART V.

SOURCES OF ELECTRICITY.

CHAPTER I.

ELECTRICITY PRODUCED BY THE ACTION OF HEAT.

Development of Electricity by Calorific Action in bad Conductors.

AFTER having studied the properties of electricity, both in respect to the general laws, to which it is subjected in its different forms, as well as in respect to the effects that it produces in bodies, while traversing them, it remains for us to examine the various means, by which it is brought into being. The sources of electricity are of three kinds, action of heat, mechanical action, and chemical actions. We are about to examine summarily these different sources, in endeavouring to discover the laws, that regulate the development of the electricity, to which they give rise; then, after having studied them, we shall seek for what they have in common, and for the general principles, by which they are connected with each other, at the same time that we shall introduce certain phenomena, in which there is production of electricity, without apparent cause. We shall commence this study by the action of heat, considered as a source of electricity; seeing that, of the three sources, it is the one which is the least complex. We shall not occupy ourselves in this Part with the natural sources of electricity, which will form the subject of our study in the Sixth Part of this work.

The influence of heat upon electricity was noticed from the earliest times, when attention was directed to electrical phenomena; it was very speedily noticed that elevation of

temperature facilitated the liberation of electricity, produced by friction in glass and insulating bodies, as we shall see in the following Chapter. Furthermore, elevation of temperature is sufficient of itself, without any other action, to render bodies electrical, which were not so. This property, proved for the first time, in tourmaline, was recognised to belong to other crystals, and has received the name of *pyro-electricity*, in order to distinguish it from *thermo-electricity*, a denomination that has been reserved to the collection of electrical phenomena, developed by heat in conducting bodies, and which will form the subject of the following paragraphs.

Pliny had already spoken of a hard, violet or deep-red stone, which, when heated in the sun, or rubbed with the fingers, attracts small light bodies. At the end of the seventeenth century, some Dutch merchants brought from the island of Ceylon a stone, to which naturalists had given the name of *tournamal* or *ashes-attractor*; and which, when placed upon hot ashes, attracted them, and immediately repelled them, whilst it manifested no similar phenomena upon cold ashes; this mineral was the tourmaline. Æpinus, having had in his hands, in 1757, two polished tourmalines, intended for setting in a ring, was the first to make a series of experiments; which established in a precise manner the laws of the development of electricity by heat in this crystal. He first proved the presence of free electricity in the heated tourmaline, by the attraction and repulsion, that it exercises successively, upon a light body, suspended by a silk thread; he even drew from it a spark, visible in the dark; but, the most important observation that he made, was that of the simultaneous presence of the two electricities in the same tourmaline, one of them being confined in one part of the crystal, and the other in another; these two parts, constituting the two opposed electric poles of the tourmaline. Æpinus had thought he was able further to lay down, as a general rule, that the electric poles, in the unequally heated tourmaline, are contrary to what they are in the equally heated tourmaline; he had had, on this point, some contests with Wilson; and, in general, there remained

many anomalies to explain, when Canton succeeded in discovering an important principle, by means of which it was easy to explain all the apparent contradictions, that existed among philosophers, upon this subject. This principle is, that it is not the absolute temperature, but the change of temperature, that renders the tourmaline electric; and that the electricity of each of its poles varies, according as this change is a heating or a cooling. More recently Bergmann took up Canton's important observation, and analysed with much clearness the various electric phases of the tourmaline, which he explained in a very satisfactory manner. Thus, a tourmaline, placed in a medium, the temperature of which it possesses, is not electrical. Transported into a colder medium, to which it abandons its heat, it acquires two contrary electric poles; a state, which again ceases, when the tourmaline has acquired the temperature of the medium. On being brought back into the former medium, the tourmaline again becomes heated, and regains its electric poles; but with contrary signs to those of the former poles, the pole that was positive during the heating, becoming negative during the cooling, and reciprocally. This law is not only true for the crystal as a whole, but also for each of its parts separately; so that if the two poles are so arranged that, one is heated while the other is cooled, they have the same electricity at the same time.

To sum up, the electric state of the tourmaline may vary in six ways, namely, if we call A and B, the two poles: —

A positive, and B negative.
A negative, and B positive.
A and B positive.
A and B negative.
A positive, and B not electric.
A not electric, and B negative.

The first state having been observed, when the tourmaline has been transferred from a cold into a warm medium; the second is observed when, after having plunged the crystal into a warm liquid, it is allowed to cool, after having been

withdrawn from it. The third state is obtained by holding the extremity B, for half a minute in the flame of a lamp or a taper; because, as soon as it is withdrawn, B cools, and A, on the contrary, becomes heated by conductibility; but when once A has acquired the highest temperature, to which it can attain, it cools and becomes negative, whilst B remains positive. The fourth state is obtained in the same manner as the third, by heating A instead of B. In order to bring about the fifth and the sixth, we have merely to place the crystal upon an insulated sheet of iron, maintained at a constant temperature, by means of a hot fire, and to cover the upper face with a cold piece of metal. The face, that rests upon the plate of hot sheet-iron, preserves a constant temperature, and possesses no electricity; whilst the other, which receives heat by conductibility, becomes electric, either positively or negatively, according as it is the face A, or the face B.

Bergmann has further demonstrated that the quantities of positive and negative electricity, developed in the crystal, are exactly in the same proportion; he has, in fact, proved that an insulated metal vessel filled with hot water, does not become electric, when a tourmaline is plunged into it; a proof that the two contrary electricities, which it acquires, neutralise each other, and that, consequently, they are equal.

We are indebted also to Canton for a very important observation; it is that, when we operate no longer upon flat tourmalines, like those, which are employed as stones or rings, but upon elongated tourmalines, whose poles are at the distance of $\frac{2}{5}$ in. at least from each other, we find, on breaking the stone into, for instance, two or three fragments, that each of them has two poles, like the entire crystal, and that the extremities of the fragments, that were in contact, before the rupture, present contrary poles. The mechanical division of a pyro-electric crystal may be carried on as far as we please, without causing the contrary electricities of each fragment to disappear. Brewster, having reduced a tourmaline into very fine powder, observed that this powder remained attached to a glass plate, upon which

he had placed it, as soon as he heated the plate; and that the small grains, when they were shaken, agglomerated into globules; a property, that disappeared, as soon as the elevation of temperature ceased to take place. Seen under the microscope, this impalpable powder presents small angular fragments, which, like the entire crystal, are endowed with electric poles, as soon as they are subjected to a change of temperature.

When a tourmaline is placed so that its lower and its upper extremity are the places of the two electric poles, every vertical line that joins these two poles, is termed the *electric axis* of the crystal. A plane, that cuts the crystal perpendicularly to the axis, determines two faces, which equally become contrary poles, either one to the other, or to that, which already existed upon the other face of the same fragment. Under this relation, the tourmaline may be compared, either to a magnet, in Colombo's theory*, or, still better, to a dry pile†; which when it is divided into two, in any part of its length, always presents two opposite poles. The analogy is so complete, that, with a dry pile, all the phenomena, presented by the tourmaline, may be imitated. Thus, if two dry piles are applied one against the other, by their similar poles, we have, at the other two free poles, the same electricity, in the same manner, as we have the same electricity at the two extremities of the tourmaline, if one of them is subjected to an elevation and the other to a reduction of temperature. Wilke, having heated a tourmaline on one side with the solar rays, concentrated in the focus of a lens, found negative electricity at the two poles, and positive at the middle.

In order to observe the different electric phenomena, that are presented by the tourmaline, we may place it, as Becquerel did, in a little stirrup of paper, suspended at the extremity of a thread of the cocoon, fixed vertically in a glass cylinder, itself placed upon a plate of metal, the temperature of which is raised (*fig.* 263.); in proportion as the interior of the vessel is heated, the temperature of the tourmaline rises;

* Vol. I. p. 194. *fig.* 78.
† Vol. I. p. 52.

and immediately that it becomes electric, we have merely to present to it a body feebly electrised, in order to observe the

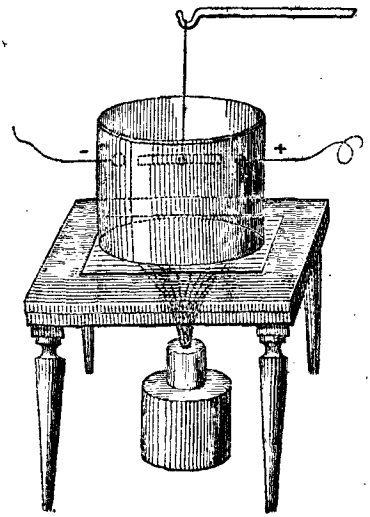


Fig. 263.

attractions and repulsions. In order the better to seize upon the changes of polarity in the tourmaline, which are sometimes very brief, we must place in the interior of the bell-glass, and at a little distance from each extremity of the crystal, two vertical metal rods, which communicate respectively with one of the poles of a dry pile; immediately that the tourmaline becomes electric, it places itself between the two rods, the contrary poles facing; it is thus easy to prove its electric state and the nature of its poles.*

* A very curious fact, which M. Becquerel has proved by means of the same apparatus, is the electric polarity, that may be acquired by a body, a bad conductor, placed under the same circumstances, as the tourmaline, when an electrised body is brought near to it. Thus, if we place in the paper stirrup a small tube of a glass, that is not very hygrometric, about $\frac{1}{35}$ in. in diameter, and about $\frac{1}{2}$ an inch in length, and present to it a rod of electrised gum-lac, it is attracted, in consequence of the decomposition of its natural electricity. On raising the temperature to 86°, the tube acquires electric polarity, which disappears as soon as the electrised rod of gum-lac is removed; but, if we cause this polarity to occur at the moment when, after having extinguished the

Riess and the German philosophers, who have been much occupied with pyro-electric phenomena, have adopted a denomination, which appears to us very happily chosen, for distinguishing the two poles of the tourmaline, and of pyro-electric crystals in general, from each other. He calls that the *analogous* pole, for which the sign, that represents the variation of temperature, and the nature of the electricity, are similar; and *antilogous* pole, that for which these signs are contrary. Thus, the analogous pole is that which is electrised +, when there is elevation of temperature, and — when there is reduction; and the antilogous, that which presents the opposite phenomena. It is very easy to determine, by means of an ordinary electroscope, the electric nature of the two poles; but it is less easy to find their exact position, as well as that of the electric axis. The natural, or artificial faces, by which the crystal is bounded, frequently cut its axis under acute or obtuse angles; and then we have, not the poles themselves, but places which are near to them, and which are frequently limited by edges or angles, where the electricity, developed at the poles, is accumulated. It results from this, that very frequently the points where the indication of the electroscope discloses the largest amount of electricity, are only places favourable to the accumulation of electricity; and that they are frequently very near to the electric pole, and not this pole itself. Sometimes deformations and fissures, due to the alteration of the crystal, become the origin of a particular distribution of electricity, which might give rise to errors, as to the place of the poles and of the axis. Thus, unless we find by chance faces perpendicular to this axis, it is necessary, in order to determine its position, to refer to crystallographical or optical measurements.

Tourmaline is not the only pyro-electric crystal. Canton had already found the same property in the topaz of Brazil; Brard, in axinite; Haüy, in boracite, scolezite, titanite, &c.;

lamp, the polarity commences, it endures for a longer or shorter period, even when the electric source, by which it had been produced, has disappeared. We have merely to heat again the medium, in which the small glass tube is, in order that the polarity may disappear.

Brewster, in mesolite, quartz, and in some artificial crystals. The electric phenomena are manifested in an almost similar manner, in all these crystals; thus their detailed study would not present any interest, if there did not exist an intimate connection between the form of the crystals and their electric polarity. Haüy was the first to point this out. He had remarked that the crystallised mineral substances, which present pyro-electric phenomena, are those, the crystals of which deviate from the laws of symmetry; namely, whose corresponding opposed parts are not similar by the number, the arrangement, and the form, of their faces; the summit, that is most furnished with facets, being that which gives positive electricity by cooling. More recently, this observation has been confirmed and studied by Kohler, by Hankel, by Rose, and by Riess. All pyro-electric crystals have for their polar faces a form, that is due to the combination of a homo-hedric form, with a hemi-hedric form. We know that the *homo-hedric* and *hemi-hedric* forms themselves result from the combination of two simple forms; in such a manner that, for the first, all the faces of one of the forms are combined with all those of the other; whilst, for the second, half of the faces of one of the forms are wanting. We have a very simple example of this in the combination of the cube with the octohedron; in the homo-hedric state, this combination presents a cube, the eight angles of which are truncated, whilst, in its hemi-hedric state, it represents a cube, the four angles of which alone are truncated, alternating with perfect angles. Now, in this case, the combination of the homo-hedric with the hemi-hedric form, which produces the polar face of a pyro-electric crystal, engenders a tetrahedron, by the reunion of the four faces, which have taken the place of the angles of the cube. But, if it is necessary, in order that a crystal may be pyro-electric, that it shall have hemi-hedric polar forms, it does not necessarily follow from this that all those which have these forms are pyro-electric.

When we desire to study the pyro-electricity of various crystals, which have not all, as the tourmaline may have, an elongated form, we cannot employ Becquerel's process,

described above (*fig.* 263:). We then make use advantageously of a dry-pile electroscope, furnished with a gold-leaf, which is carried by a rod in the form of a truncated cone, the upper surface of which receives the electric face of the crystal. It is necessary to pay great attention, so as to avoid all friction, on placing the crystal down; for, without this precaution, negative signs are frequently obtained, which are due to the friction of its faces. The crystal is taken with pincers, lined with cork, which must be covered with tin-foil, to prevent its retaining electricity. In order to collect the electric signs, that accompany the cooling of the crystal, the precaution is taken of heating it in a porcelain crucible filled with leaden shot, as fine as possible, which is placed in communication with the ground, by means of a conductor, in order to cause the electricity to disappear that is produced by the heating, and which might remain adhering to the surface of the crystal. It is left plunged in the shot for a longer or shorter time, according to its mass, in order that it may acquire the temperature, indicated by the thermometer, which is also placed in it. In order to cause the electricity to disappear, which may be developed upon its surface by the friction, that it suffers from the shot, at the moment, when it is withdrawn from it, the precaution must be taken of causing it to pass rapidly through a spirit-flame.

In general, the experiments are better made, by observing the electricity, that is liberated during the cooling, than that, which results from the heating, seeing that the heating can never be brought about with so much regularity as the cooling; however, the results obtained may be controlled, by heating with a spirit-lamp one of the extremities of the crystal, whilst the other is in communication with the electroscope. But we are not able in this way to determine the position of the electric poles, we merely obtain information, as to the nature of their electricity.

If we now apply the experimental processes, that we have been describing, to the study of the pyro-electricity of various crystals, we arrive at some interesting results, of

which we shall confine ourselves to pointing out the most important.

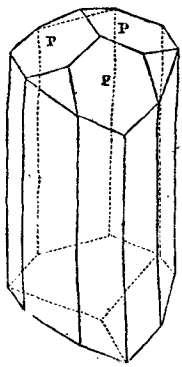


Fig. 264.

The tourmaline, for the most part, assumes the form of a nine-sided prism (*fig.* 264.); produced either by a three-sided prism, whose edges have two small faces, or by a six-sided prism, the three edges of which are each replaced by a face. The extremities of the prism are formed by three faces of the principal rhombohedron, or simply by the faces of the fundamental prism of three tables. The faces of the principal rhombohedron rest at one of the extremities of the crystal upon the faces, and at the other extremity upon the edges of the three-sided prism. The former of these extremities is the *analogous* electric pole, the latter the *antilogous* pole; the lateral edges of the prism represent the direction of the axis. Sometimes the principal rhombohedron is wanting; but its position may be appreciated from the other terminal faces. The intensity of the electricity, in the same conditions of temperature, varies with each specimen of the crystal; it is in general greater in tourmalines of clear colours and pure and transparent mass; however, very electric tourmalines are sometimes found among those that are black and not transparent. The dimensions of the crystal also influence the energy of its electric properties, the thicker and the longer being those in which this energy is the greatest.* The tourmaline in general gives only electrostatical effects. However, Du Bois-Reymond succeeded in obtaining an electric current by pressing between two plates of platinum, communicating with the ends of the wire of a galvanometer, the two poles of a black tourmaline an

* However, M. Becquerel has remarked, that the fragments obtained by the rupture of a rather long, but thin tourmaline, are more powerfully electric than the entire tourmaline was. He has even found one tourmaline which, not being electric, gave, on being divided into two, fragments that manifested decided signs of electricity.

inch in length, by $\frac{1}{4}$ of an inch in thickness, which he heated with a spirit-flame; the deviation of the galvanometer took place in a contrary direction when, instead of heating the tourmaline, it was cooled by moistening it with sulphuric ether. The current came from the analogous pole during the heating, and from the antilogous pole during the cooling. It is probable that this tourmaline was of a more conducteous nature; which occurs with opaque tourmalines, that contain some metallic oxides, the presence of which is probably also the cause of their less aptitude to become charged with static electricity.

Mr. Forbes, who made a great number of experiments upon this subject, found a crystal of tourmaline, the structure of which appeared regular to the sight, but which possessed the extraordinary property of presenting, on cooling, a positive electric pole at each of its extremities. But he observed that the central portion of the crystal possessed an excess of negative electricity. Everything leads to the belief that this crystal was a mascle, namely, a crystal formed of two others, attached together by the symmetrical faces, which possess consequently the same electric polarity. Mr. Forbes, in the numerous specimens, that he has examined, found, contrary to M. Becquerel, that, in general, the longest pieces of tourmaline are those which give the most intense electric signs, for an equal section; but there does not appear to exist any relation between the length and the intensity.

Silicate of zinc is one of the most perfectly electric crystals; the slightest change of temperature is sufficient to render its electricity sensible. Its analogous pole is the only one, that is perfectly crystallised; the antilogous pole is in general truncated, and very rarely presents natural faces, seeing that the increase of the crystal is brought about by this extremity. Moreover, the two polar extremities, as in all electric crystals, have a different crystallisation. The premature form of silicate of zinc is a rectangular octohedron; but it presents itself in hexahedral prisms with dihedral summits.

Scolezite (silicate of lime and alumina*) presents itself under the form of crystals grouped together so as to possess only one extremity regularly crystallised, which is pyro-electric and forms the antilogous pole, whilst the analogous pole would be at the free extremity, and where the ramifications converge; but the crystallised bundle resolves itself more frequently, at the point of convergence, into a compacted fibrous mass, which is not electric, and which becomes so only at the place, where the crystallised needles may be distinguished fairly formed; its electric axis is confounded with its crystalline axis. Scolezite, which is very easily electrisable, is still more so, as Sir D. Brewster has remarked, even when heat, by removing from it its water of crystallisation, has converted it into a white powder; which proves that it is to the particles alone of the crystals, and not to their mass, that the pyro-electricity appertains. It frequently happens that the crystals of scolezite, being mascles, the extremities, that have opposite poles, are connected, and there is no sensible development of electricity by heat; but, if one of the crystals, which form the mascle, is removed by polishing, the other is always electric.

Axinite (silicate of lime and alumina†) is feebly electrical. It is necessary to heat it up to 248°, in order to obtains signs of electricity; and certain specimens even, although very

* Composition of scolezite: —

Silica	46·25
Alumina	24·82
Lime	14·20
Soda	0·39
Water	13·64
	99·30

† Axinite contains less alumina and more lime than scolezite. The following is its composition: —

Silica	43·686
Alumina	15·630
Lime	20·670
Ferric oxide	9·450
Manganic oxide	3·050
Magnesia	1·700
Potassa	0·640
Boric acid	5·610
	100·436

well crystallised, sometimes do not give any. In general, the antilogous poles are more energetic than the analogous. It would seem that axinite is formed of two crystals, in which the electrical axes have an opposite direction.

Boracite (borated magnesia) is powerfully electric. It possesses four electric axes; the four antilogous poles are upon the brilliant faces of the tetrahedron, and the four analogous poles upon the angles of the cube; for boracite presents itself to us under the form of a cube, modified, for the most part, on the edges and on the solid angles; so that these latter completely derogate from the law of symmetry. Reduced into powder, boracite is still electric, although we are unable, by the microscope, to discover crystalline forms in the grains of the powder that it forms. Boracite seems to present an exception to the general law, that opposite electricities are manifested at the same pole, only so long as there is an inversion in the march of the temperature. In fact, on heating boracite in leaden shot with all possible precautions, we see the antilogous pole, for instance, constantly give negative electricity with a temperature ascending up to 400°; it then gives positive from 400° to 493°; with a descending temperature, it gives negative from 460° to 413°, and returns to its normal state, giving positive below 413°. This exception is probably only apparent, seeing that it is manifested the more easily, in proportion as the mass of the crystal is less homogeneous. A difference in the structure of the envelope of the crystal, and in that of its nucleus, is necessarily accompanied by a difference in conductibility for heat, and in the development of the electricity of each of the two parts. As soon as the boracite is taken out of the crucible in which it has been heated, in order to expose it to the air, the surface is easily cooled, and covers a nucleus still hot; so that the electroscope should indicate the difference between two opposite electricities; namely, that of the envelope, which receives heat from the central nucleus, and that of this nucleus, which is cooling. Negative electricity comes from the nucleus; also, in order that the electricity which comes from the envelope may preponderate, it is necessary to heat the latter very powerfully.

It may happen that the electroscope manifests no electricity, as takes place also after the most powerful heating for tourmaline, axinite, and topaz; which is due, equally in all these crystals, to the electricity of the nucleus being disguised, at the commencement, by that of the envelope, which is of a contrary nature. Now, it is found that this latter may preponderate over the former in boracite, on account of the particular structure of the crystal, and its facility of becoming electric.

Rhodizite greatly resembles boracite, in respect to its form, and its manner of being in its electric relation; so that we need not occupy ourselves with it.

Prehnite (silicate of lime and alumina*) presents in its pyro-electricity a peculiar character; it is, that its two electrical axes are turned towards each other, in such a manner, that the analogous poles are confounded into a single one, whilst the antilogous are distinct; which causes the crystal to be tripolar. Thus the little diagonal of the base gives the direction of the two axes; the common analogous pole of which is in the middle of this line, whilst the two antilogous poles are at its extremities; and this is the case for the entire mass of the crystal. It follows from this, that the lateral edges of the truncated base possess antilogous electricity in all their extent, whilst the analogous electricity is found in the middle of the face. The crystals, whose electric poles are thus arranged, are called *centri-polar*.

The *topaz* (fluosilicate of alumina†) is a crystal of the

* The following is its composition, which differs notably from that of scolezite and axinite: —

Silica	44·10
Alumina	24·26
Lime	26·43
Protoxide of iron	0·74
Water	4·18
	99·71

There are some varieties which contain less lime, and more protoxide of iron.

† The following is the composition of the topaz: —

Silica	34·36
Alumina	57·74
Fluoric acid	7·77
	99·87

same kind; it also possesses two electrical axes in the direction of the shorter diagonal of the base of the prism. The two analogous poles are in the middle of the short diagonal; the two antilogous poles are in the truncated lateral edges. A topaz, that might have a complete form, namely, that of a prism with four faces, with pointed extremities of four tables, would not be electrical at its two extremities; but the antilogous electricity would be presented on the lateral truncated edges, in all their extent; and thence would rapidly diminish on the lateral faces, and would disappear toward the sharp lateral edges, as well as upon the edges themselves. There would not be any analogous electricity on the whole surface of the crystal; it would all be interiorly. But, in fact, topazes deviate much from this normal character. On altering a sharp lateral edge, we provoke the presence of analogous electricity; the terminal edges themselves receive electricity from the electric points, that are nearest to them; and the terminal point, when it is truncated, which is the common case, liberates a feeble analogous electricity. It follows from this, that the distribution of the analogous and antilogous electricities is singularly modified in the topaz, either by natural irregularities in its crystalline state, or by those that are brought about by artificial ruptures.

Mr. Forbes, who has studied the pyro-electricity of the topaz and of boracite, has found, as M. Becquerel had before remarked, that the intensity of the electricity attains its maximum, when the velocity of the cooling has become comparatively more feeble. He has observed, in particular, that topaz possesses the property of preserving its electricity for a long time after the temperature has ceased to suffer changes. This effect depends simply upon the conductibility of the stone; for we may very well conceive, that it might happen that the crystal, becoming a worse conductor, in proportion as the heat diminishes, the recomposition of the two electricities requires more time for being brought about. Thus, having obtained a deviation of 115° of the needle of Coulomb's torsion electrometer, on presenting to it a crystal of tourmaline, a few instants after it has become electric by heat, at the end of 20″ the deviation was scarcely diminished;

at the end of 40″ it was still 95°; at the end of 60″, 85°. After several hours, the metal was still powerfully electric. Mr. Forbes has obtained similar results with several other crystals; it appeared to him, from his researches, that, in all minerals, the difficulty which the two electricities experience in separating, and consequently in recombining, increases with their mass; hence it follows that thin crystals are more easily electrical by heat, but remain so for a shorter time.

Titanite, heavy spar, and *rock crystal* give, in some cases, signs of pyro-electricity; but these signs are not at all regular; and we have not yet succeeded in determining the electric axes of these crystals.

A very great number of crystals, besides those of which we have spoken, have been carefully examined by MM. Rose and Riess, and have not manifested any traces of pyro-electricity; but these negative results are not entirely conclusive. Indeed, among pyro-electric crystals, we frequently find specimens that are not so; either in consequence of some cause that increases their interior conductibility, or by a mode of groupment of their integrant molecules, which disguises the electric state that is developed in these molecules by the movement of heat. It may therefore happen that, among the crystals which have not hitherto appeared to be pyro-electric, specimens occur that are of a nature to be so.

Independently of natural crystals, many artificial ones are found, which are also pyro-electric. One of the principal is *struvite,* which is an ammoniacal phosphate of magnesia, formed by the prolonged decomposition of animal matters. The struvite is a vertical rhombohedric prism, terminated at one of its extremities by a plane surface, and at the other by the faces of a transverse prism. It has a single electrical axis, which is in the direction of the vertical prism; the analogous pole is at the right terminal face, and the antilogous is at the edge of the transverse prism of the other face. The crystal becomes easily electrical; the heat of the hand is sufficient to render the electricity of its two poles sensible.

Besides the crystals that we have just named, three others, also artificial, among all those that Brewster has studied,

have been generally recognised as pyro-electric; these are *sugar*, and the two *racemic acids*. Care must be had not to take the ordinary racemic acid, for it is very little pyro-electric; whilst uvic acid, which, in its chemical relations, is similar to it, is very powerfully so. This is due, as M. Pasteur has demonstrated, to racemic acid being formed of two acids chemically identical, but which are dissymmetrical in their molecular relation; one causing the plane of polarisation to turn to the right, and the other causing it to turn to the left. Now, these two acids, the former of which is identical with uvic acid, are equally endowed with a very powerful pyro-electricity; they have a single electrical axis in the short diagonal of the base of the prism.

To sum up: it follows, from the detailed study, that we have been making of the pyro-electricity of crystals, that this phenomenon is much more general than has been supposed; but that it takes place only, so long as the substance is in the crystalline state; and that it requires for its manifestation a dissymmetry in this state. We may add, that the property, which gives rise to the phenomenon, belongs not to the mass, but to each molecule of the crystal; that it is very probably due to the manner, in which the atoms are grouped, in order to form the integrant molecule, and to the rupture of electric equilibrium, which is imparted to this molecule by the motion of heat.

M. Becquerel conceives, also, that there is brought about by heat in crystals a dilatation, that separates the planes of cleavage; which produces a liberation of electricity analogous to that which takes place in cleavage, as we shall see in the following Chapter. Indeed, when a topaz is split in the direction, perpendicular to the axis, the two separated faces are found to be in two different electrical states; so that we are able to conceive heat as operating a species of cleavage, and liberating the two electricities, which would seem to be disguised before the rupture.

We shall, however, return, after having studied the electric effects of heat in conducting bodies, to this remarkable influ-

ence of the arrangement of particles in pyro- and thermo-electric phenomena.

Liberation of Electricity by Calorific Action in good Conducting Bodies.—Thermo-electric Currents.

M. Seebeck discovered, in 1823, that an electric current may be brought about in a circuit entirely metallic, by simply establishing a difference of temperature between one point of this circuit and the others. The first experiment was made by forming, by means of a bar of bismuth *s s*, and a plate of copper *s c s*, soldered end to end, a kind of arc (*fig.* 265.); in the interior of which, a magnetised needle *a b*, rested by its cap upon a point. The apparatus being placed in the direction of the magnetic meridian, in order that the needle, freely suspended, might be parallel to the two pieces of metal between which it was placed, it was merely necessary slightly to heat with a spirit-lamp one of the points of soldering, in order to obtain in the whole of the circuit an electric current, the presence of which was detected by a distinct deviation of the needle. The direction of the deviation, and consequently of the current, changed, according as it was one or the other of the two solderings, that was heated; it changed likewise when, instead of being heated, the same soldering was cooled. It is therefore necessary to establish a difference of temperature between the two solderings, in order that a current may be established; if they are exactly at the same temperature, there is no effect.

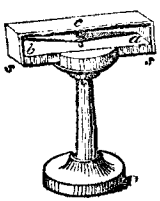


Fig. 265.

Seebeck gives the name of *thermo-electric* to this current, and to the pair, by which it is generated, in order to distinguish it from the current, and from the *hydro-electric* pair, otherwise called voltaic current and pair.

Seebeck further remarks that, on substituting a bar of antimony for the bar of bismuth, but taking care still to retain the plate of copper, the direction of the current becomes inverse, under the same circumstances, from what it was in the

former case; thus, with copper and bismuth, the current is directed from the bismuth to the copper through the heated point, and consequently from the copper to the bismuth through the point not heated; and with copper and antimony it is directed from the copper to the antimony in the part heated, and from the antimony to the copper in the part not heated. Also, in order to obtain the greatest effect, it is necessary to form the thermo-electric pair of a bar of bismuth (*fig.* 266.), in the form of an arc $s\,c\,s'$, the two extremities of which rest upon the two extremities of a bar of antimony $s\,s'$. For the needle of the former apparatus is substituted an astatic needle, the axis of which passes freely through an opening made in the middle of the plate of bismuth. When the apparatus has been arranged in the magnetic meridian, we have merely to pinch between the fingers the two metals, at one of their points of contact, in order to bring about between this point and the other, a difference of temperature, capable of causing the needle to deviate several degrees.

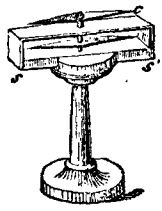


Fig. 266.

Seebeck further succeeded in producing thermo-electric currents, by composing the two parts of the pair of a same metal; but he only succeeded with metals that have a very decided crystalline texture, which establishes a difference of homogeneity between their different parts; or with two portions of the same metal, rendered directly heterogeneous, such as two pieces of steel, one soft, the other tempered.

Taking up this last part of Seebeck's researches, various philosophers succeeded in producing thermo-electric currents in homogeneous bodies. Yelin showed that, we have merely to heat one of the extremities of a bar of bismuth, in order to act upon a magnetised needle, on placing it parallel above or below this needle; the direction of the deviation varies according as the hot or the cold extremity of the bar of bismuth is brought near to the needle; the same results are obtained for each of the extremities of the bar, when it is heated at its middle, and when its extremities are retained

cold. Yelin further recognised, that the thermo-electric action of metal bars depends upon the form, that has been given to them by casting, and upon the manner in which they have been cooled in their different parts, which enables us to detect a relation between crystallisation, or generally between the molecular constitution of metals, and this class of properties. It is evident that the difference of temperature, between the various points of these large metallic masses, determines the production of currents upon their surface, which act upon the needle in a manner analogous to the induction currents, that are produced upon a disc, or upon a rod of metal, by approaching to it a magnet. Only the thermo-electric currents are not instantaneous, like those of induction. With regard to the direction of these electric currents, it is evidently connected with the direction of the propagation of the heat, and with the form and internal texture of the metals, submitted to experiment.

Mr. Sturgeon obtained more precise results with cylindrical and conical bars, either of bismuth or antimony. The currents were, in general, directed from the hot to the cold part, at least in cones, whose base was heated or cooled. In cylinders, the distribution of the current was very regular. On heating uniformly one of the extremities of a cylinder of antimony, two neutral lines were found determined on the surface by a plane passing through the axis of the cylinder, and currents were directed along others generated from the cylinder. Mr. Sturgeon also made a great number of experiments on homogeneous rectangles and rings of metal; but, before explaining them, we must speak of the important results, that M. Becquerel had long previously obtained.

M. Becquerel's process is altogether different from those employed by Seebeck and by the philosophers, of whom we have spoken. He operated, by means of a multiplier, taking care to use one with a thick and short wire, in order that the thermo-electric currents, produced in a circuit all metallic, shall not encounter too great a resistance, in their course through the wire of the instrument. Having coiled into a spiral the two ends of the copper wire of the multiplier, he

showed that, in order to produce a current, nothing more was needed than to heat one of these ends in a spirit-lamp, and to touch it with the other, that remained cold; on separating the two spirals, and renewing the contact at each oscillation of the needle of the instrument, very considerable deviations were obtained. Wires of platinum and of silver give rise to the same phenomenon as the copper wire, except as regards intensity, which varies with the metal employed; thus, with platinum, one of the spirals must be raised to cherry red, the other remaining at the ordinary temperature; whilst with copper wire, it is not necessary to heat it beyond nascent red, in order to obtain a very sensible current. M. Becquerel, in his first experiments, had constructed with each of the wires submitted to experiment, a complete galvanometer-multiplier; but this is not necessary; we have merely to fix at each of the extremities of the copper wire of an ordinary galvanometer, a piece of the wire upon which we desire to operate, using the precaution of taking these ends of sufficient length, that the heat may not propagate in a sensible manner, as far as the point, where they are in contact with the wire of the galvanometer. We may add that, in the preceding experiments, the current was directed from the heated extremity to the extremity that remained cold, through their point of contact; and consequently from the cold to the heated, through the wire of the galvanometer.

It would seem, from what precedes, that it would be sufficient to connect by a wire the two ends of a galvanometer and to heat this wire in any point of its length, in order to obtain an electric current. Now, M. Becquerel has remarked that, whatever be the nature of the connecting wire, no effect is obtained, on operating in this way, at least if the wire is sufficiently long, and the heated point at a sufficient distance for the heat not to arrive as far as its points of contact with the wire of the galvanometer. But if, without disturbing the homogeneity of a platinum wire *a b c* (*fig.* 267.), we make a knot, or better still, coil it into a spiral at *o*, in a part of its length, at the same time producing no point of discontinuity, and apply the focus of heat, at a short distance

from this spiral, a continuous current is obtained directed from the side of the swelling, setting out from the heated

Fig. 267.

point, which is probably due to the small mass being heated at the expense of the heat, transmitted by the portion $f\,i$ of the wire, that separates it from the focus. It is very evident that if a distance $f\,i = f\,i'$, is taken at i and i', the movement of the heat cannot be the same on account of the mass o, and the current must arise from the difference of these two movements. Palladium comports itself in the same manner as platinum: a gold wire does not produce any effect; a silver produces but a very feeble effect; as is also the case with a copper wire. A continuous current, however, may be obtained by uniting the extremities of the galvanometer with a copper wire, that is cut in two, and the free ends of which are united, by means of two hooks, passed one into the other (*fig.* 268.). The spirit-lamp is placed on the right or on the left of the junction point, at b, for example; and a current is obtained, which follows the direction $a\ b\ c$, which is probably due to the propagation of heat taking place more easily, in this direction, than in the other. This explanation appears the more plausible, as the oxidation of the copper wire, at the point of junction of the two ends, which is a consequence of the heat that arrives there, increases the intensity of the current, by diminishing the facility of the propagation of heat, in this part of the circle.

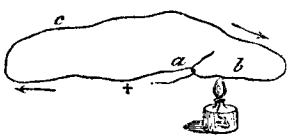


Fig. 268.

Led on by these experiments, and by others of the same kind, M. Becquerel admits, as a fundamental principle, that the propagation of heat in a metal — in a wire $a\ a'\ a''\ a'''$ (*fig.* 269.), for example — is always attended by a liberation of electricity; a liberation that consists in this, that the first particle a, which

is in contact with a source of heat b, takes from this source the positive electricity, leaving to it the negative; that, in its

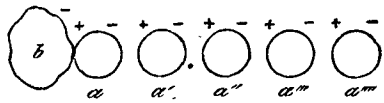


Fig. 269.

turn, the second particle a', on becoming heated, takes in like manner positive electricity from the first up to the last a''', which is thus found charged with positive electricity. This propagation is naturally made by means of the electric polarisation of the successive particles, and by a series of decompositions and recompositions of the contrary electricities of these consecutive particles, in such a manner that there is no free electricity, except at the two extremities; thus, if we touch the incandescent end, namely, the particle a, with a conducting body, sufficiently large not to be sensibly heated, we take away its positive electricity, the negative of a takes the positive from a', and so on to the particle a''', which is found to retain negative only.

M. Becquerel has endeavoured to prove directly this principle, by means of the following experiment. He introduces a platinum wire $a\ b$ (*fig.* 270.), into a glass tube, closed by

Fig. 270.

the lamp at one of its extremities, and makes the free end communicate with the plate of a condenser; he then coils around the closed end of the tube another platinum wire $a'\ b'$, the free extremity of which communicates with the ground; he heats powerfully the end of the tube, and then the interior wire transmits to the condenser a very sensible charge of positive electricity.

In order to explain this production of electricity, M. Becquerel observes that the glass tube, becoming a conductor by means of its elevated temperature, the positive electricity of the exterior wire traverses the glass and is conducted to

the condenser by the interior wire; the latter, it is true, ought to produce an inverse effect; but, being less heated, the effect of the former, to which the flame of the lamp is applied directly, preponderates over that of the latter; if the two wires were equally heated, there would be no effect at all. We may remark, that the negative electricity of the exterior wire is carried to its cold extremity; and thence into the ground, with which it communicates.

The interpretation that we have just given of M. Becquerel's experiment is subject to many objections. M. Gaugain has shown that the employment of the spirit-lamp may give rise to electro-chemical currents; and, even supposing that we succeed, as M. Leroux has done, in avoiding the production of these currents, we cannot protect ourselves from the electricity that may arise from the action upon the platinum of the melted or of the less heated glass. Whatever may be the case, setting out from the principle that the propagation of heat is accompanied by a liberation of electricity in each metal, M. Becquerel hence concludes that, when we heat in any point of its length, a perfectly homogeneous wire, by which the two ends of a galvanometer are connected, there should be established, setting out from the heated point, two currents perfectly equal, travelling one to its right, the other to its left, and returning to their point of departure, after having traversed the galvanometer; these two equal currents being guided in contrary directions, their action ought to be null, as demonstrated by experiment. But, provided the homogeneity of the wires be disturbed on one side or on the other, it follows that one of the two thermo-electric currents becomes more powerful or more feeble than the other; and their difference is detected by the deviation of the galvanometer. A very small matter is sufficient to disturb this homogeneity; according to M. Becquerel, a simple, but very slight increase of mass is sufficient; a difference in the molecular state, a feeble alteration in chemical purity is, in like manner, sufficient. M. Becquerel attributes the influence of the non-homogeneity to its bringing about a difference in the manner, in which the heat is propagated; a difference which, according to him, is sufficient to es-

tablish one between the two currents. We shall see, further on, that it is in the non-homogeneity itself, and not in the influence, that it exerts over the propagation of heat, that we must seek for the cause, which makes one of the currents to be stronger or more feeble than the other.

But, of all methods, the most efficacious for destroying homogeneity, is to substitute for the single wire, by which the two ends of the galvanometer are connected, a wire composed of two pieces of wire of a different nature, but united metallically together. On heating their point of contact, we obtain at the galvanometer a current, which is the difference of the currents that each of them would separately produce, each wire being at the same time the conductor of the current liberated by the other. In other words, the intensity of a thermo-electric current is equal to the difference of the thermo-electric actions, produced in each metal by the same temperature; so that if we call P *iron*, the thermo-electric power of iron, and P *copper*, that of copper, the intensity of the current, when the iron-copper soldering is raised to a certain temperature, ought to be equal to P *iron* — P *copper*, or to P *copper* — P *iron*, according as it might be the thermo-electric power of the iron or that of the copper, which should be most considerable. In this case, that we have just pointed out, is included Seebeck's primitive experiment of the thermo-electric pair, bismuth and copper. M. Becquerel, on forming similar pairs with various metals, and raising the temperature of their point of contact, has obtained in the galvanometer currents, which led him to arrange these metals in the following order, with regard to their thermo-electric properties: *bismuth, platinum, lead, tin, copper, gold, silver, zinc, iron,* and *antimony.* In this Table each metal is positive in respect to that which precedes it, namely, that platinum, for example, acquires positive electricity from bismuth, which causes the current to go from the platinum to the bismuth, through the wire of the galvanometer, from the bismuth to the platinum, through the heated point. But it is preferable to represent the phenomenon, as we have done higher up, namely, setting out from the principle that each of

the two metals, heated at their point of contact, gives rise to an independent current, which goes for each, from the heated point to the cold extremity, through the other metal. According to this, the order of the metals, in the above table, would be that of their thermo-electric powers, and the effect observed would be due to the difference of intensity of the thermo-electric powers of the two metals in contact.

This order differs a little, for some of the intermediate metals, from that which had been established by M. Yelin, and more recently by M. Nobili: but, more than this, these two physicists have remarked that, for some metals, such as antimony in particular, the thermo-electric power is converse of that of the others; in other words, in these metals the current, instead of being directed, as in all the others, from the heated extremity to the cold, through the entire circuit, is directed from the cold to the hot; so that, when one of them forms a pair with another metal of the series, the two currents that arise from the heating of the point of contact, instead of traversing the wire of the galvanometer, in contrary directions, traverse it in the same direction, and consequently are added together, which renders the pairs thus formed much more powerful; this is what takes place especially with the bismuth and antimony pairs.

Another anomaly, observed by M. Becquerel, is the change that takes place in the direction of the current in certain pairs, when the temperature is raised beyond a certain limit. Thus, in an iron and copper circuit, the current goes from the copper to the iron, through the heated point, so long as the temperature does not exceed a certain degree, about 572°; under the action of a higher temperature, the current changes in direction, and goes from the iron to the copper. The same change takes place, but at a lower temperature, with pairs of zinc and silver, and zinc and gold; the current which, for less elevated temperatures, went from the silver and the gold to the zinc, goes, beyond 212°, from the zinc to the silver and the gold.

We will now see the mode, adopted by M. Becquerel, for determining the relative thermo-electric power of each

metal. In order to render the comparison between metals possible, it would be absolutely necessary to place them under the same conditions; and consequently not only to reduce them to wires of the same diameter and the same length, but also to place them all in the same circuit, so as to avoid the differences of conductibility, which might influence the intensity of the currents, independently of the thermo-electric power. With this in view, M. Becquerel carefully soldered, end to end, eight wires of different metals of $\frac{1}{5\frac{1}{0}}$ th. of an inch in diameter, and about 8 in. in length; then (*fig.* 271.) he placed this chain in communication by

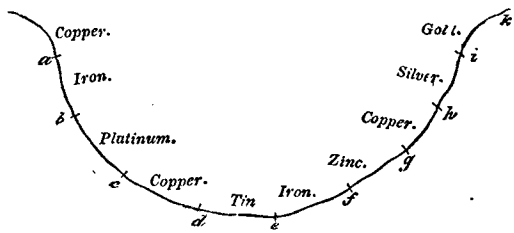


Fig. 271.

its extremities with the ends of the galvanometer. All the solderings were maintained at 32°, except that upon which the experiment was made, which was gradually heated up to 68°. By operating thus upon each of the soldering successively he obtained the following results: —

Solderings Heated.	Deviations.	Intensity of the Current.*
Iron — Tin	36·5	31·24
Copper — Platinum	16·0	8·55
Iron — Copper	34·5	27·96
Silver — Copper	4·0	2·00
Iron — Silver	33·0	16·20
Iron — Platinum	39·0	36·07
Copper — Tin	7·0	3·50
Zinc — Copper	2·0	1·00
Silver — Gold	1·0	0·50

* These intensities were deduced from the deviations, by means of a table, drawn out empirically, which gave the relations between the extents of the deviations, and the corresponding intensities of the currents.

In order to interpret the results contained in this Table, it is necessary to bear in mind, from what we have said above, that the intensity of the current of each pair is the difference between the intensities of the currents, to which each of the two metals of the pair would give rise separately; or, which comes to the same thing, that the intensities given in the Table represent the difference of the thermo-electric powers of the two metals, that compose the pair whose point of contact is heated. This important point has been established directly by M. Becquerel, by means of the following experiment.

For this purpose, the circuit of *fig.* 271. is employed, in which iron and copper are first in contact at the point *a*, and separated everywhere else, at the solderings *b* and *c*, *d* and *e*, *f* and *g*, by wires of platinum, gold, and tin. The experiments are commenced by raising the soldering *a* to 122°, whilst all the others are maintained at 32°; the intensity of the current is then observed; then, after having successively raised to 122° the solderings *b* and *c*, *d* and *e*, *f* and *g*, all the others being equally maintained at 32°. Under these different circumstances, the currents have always the same intensity; so that iron and copper, when they are in contact, or are separated by other metals, give rise to a current, whose intensity is the same; this current, consequently, depends on the temperature alone of the two extreme points.

Returning to the above Table, M. Becquerel deduced from it the thermo-electric power of the metals, setting out from the principle, that the metal, which takes positive electricity from the other at the point of contact, is the one whose thermo-electric power is the more powerful. Thus, in the iron copper pair, the current goes from the iron to the copper through the entire circuit, and consequently, from the copper to the iron through their heated point of contact; it is therefore the iron that acquires positive electricity from the copper, and it has (still according to M. Becquerel) a higher thermo-electric power. But, in our opinion, the reverse should be the case; for, the thermo-electric current

of the iron ought to go from its heated to its cold extremity, through the entire circuit, and that of the copper the same. But the definitive current, detected by the galvanometer travelling in the direction of the current of the copper, indicates that it is the latter, which is the more powerful.

Whatever the case may be, by reasoning with M. Becquerel, we obtain $27{\cdot}96 = p$ iron $- p$ copper, and $36{\cdot}07 = p$ iron $- p$, platinum. If we subtract the former expression from the latter, we obtain: p copper, $- p$ platinum $= 8{\cdot}11$; now, the Table gives, for the value of this expression, drawn directly from experiment, 8·55, a number that is very little different. In like manner, p iron $- p$ tin $= 31{\cdot}24$, and p copper $- p$ tin $= 3{\cdot}50$; whence p iron $- p$ copper $= 27{\cdot}74$, in place of 27·96, which is given by experiment. If, therefore, we designate by x the thermo-electric power of iron at 68°, we shall have

p iron	$=$	x
p silver	$=$	$x - 26{\cdot}20$
p gold	$=$	$x - 26{\cdot}70$
p zinc	$=$	$x - 26{\cdot}96$
p copper	$=$	$x - 27{\cdot}96$
p tin	$=$	$x - 34{\cdot}24$
p platinum	$=$	$x - 36{\cdot}00$

Iron is positive in respect to each of the metals of the series; it is therefore, according to M. Becquerel, its current that determines the direction of the current, which results from the thermo-electric pair, that it forms with each of these metals; it follows, therefore, from this, that its thermo-electric power is superior to that of the other metals, and that consequently x is greater than 36. With regard to the absolute value of x, it can only be determined indirectly, and by way of hypothesis. M. Becquerel remarks that when, among the calorific properties, we seek for those that are sensibly the same for the different metals, such as gold, silver and zinc, which have the same thermo-electric power, we scarcely see anything but their radiating power; indeed, it is neither the conducting power, nor the specific heat. If, therefore, we suppose that the thermo-electric powers are

proportional to the radiating powers, we are able, on comparing, under these two relations, iron and gold, whose radiating powers are as 15 : 12, to establish the following proportion,

$$x : x - 26{\cdot}70 = 15 : 12$$

which gives

$$x \text{ or } p \text{ iron} = 133{\cdot}50.$$

The thermo electric powers of the other metals are easily deduced from this; and thus we have p silver = 107·30, p tin = 102·26, and p platinum = 97·50.

But, independently of the uncertainty that reigns over the accuracy of the hypothesis, which has given us the value of x, the thermo-electric powers, calculated, as we have just done, would only be true under the conditions of temperature and conductibility of circuit, which we have employed for establishing them. M. Becquerel succeeded in relieving himself from these two elements, by remarking, that the intensities, found directly by experiment, and which give the difference of the thermo-electric powers, such as p iron — p copper, are proportional to the conducting powers of the circuit, and to the temperature; which he verified directly by experiment, forming circuits composed of two metals alone, and causing the temperature to vary within certain limits, without, however, passing beyond 122°. Setting out from these acquired points, he was able to represent the thermo-electric powers of the metals by numbers, independent both of the conductibility of the circuit, of which they form part, and of the quantity of heat, that is propagated in them.

If, as we believe, we must invert the order of thermo-electric powers, namely, regard, as having the strongest powers, that one of the two soldered metals, in which the current travels from the heated to the cold extremity, through the entire circuit, we have in the Table, that gives the value of p iron, p silver, &c.

$$p \text{ silver} = 26{\cdot}20 - x$$
$$p \text{ gold} = 26{\cdot}70 - x$$

and so on. We must then admit that the thermo-electric

powers are no longer directly but inversely proportional to the radiating powers, and instead of the proportion,

$$x : x - 26{\cdot}70 = 15 : 12$$

we have

$$x : 26{\cdot}70 - x = 12 : 15$$

Whence is deduced,

$$x \text{ or } p \text{ iron} = 12$$

And consequently p silver $= 14{\cdot}20$, p copper $= 14{\cdot}70$, p tin $= 22{\cdot}24$, p platinum $= 24$.

As we have just explained, M. Becquerel, in connecting the production of thermo-electric currents with the propagation of heat, considers thermo-electricity as a direct effect of heat, modified simply by the special conditions of the body, that transmits the calorific flux. The experiments, in the limits within which these have been made, seem to favour this opinion; and, in any case, they show, at least, for the metals, which have been the subject of them, and for the temperatures to which they have been exposed, that the thermo-electric power of a pair is really the difference of the thermo-electric powers of the two metals, of which it is formed, or else their sum, if these thermo-electric powers are the converse of each other, as is the case with the pair of bismuth and antimony, for example. This simple and important law is not necessarily connected with the hypothesis, which attributes the development of the thermo-electric power to the propagation of heat; it can be sustained, whatever be the cause of this development. Let us therefore endeavour, by new facts, to obtain an accurate idea of this cause.

We shall not, however, terminate this paragraph without describing also two elegant pieces of apparatus of Mr. Cumming's, founded upon the development of thermo-electric currents. The first is a simple rectangle (*fig.* 272.). The three sides of

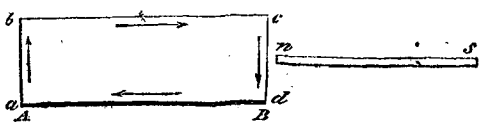


Fig. 272.

which *a b*, *b c*, and *c d*, are formed of silver wires, and the fourth A B of a platinum wire. This rectangle is suspended at *e*, in such a manner that the platinum is situated below. If we heat one of the points of junction, or A, and present to one of the sides, to the side *c d*, for example, a magnet *n s*, the rectangle is immediately seen to obey the attractive or repulsive action of the magnet, upon the current that circulates in *c d* from *c* to *d*. The metallic circuit may be suspended upon the magnet itself (*fig.* 273.), so as to allow it, by bending the platinum wire A B C, to turn around the magnetic pole, which in fact takes place, as soon as we heat, by means of a lamp, the point C, which in each revolution of the circuit passes above the flame.

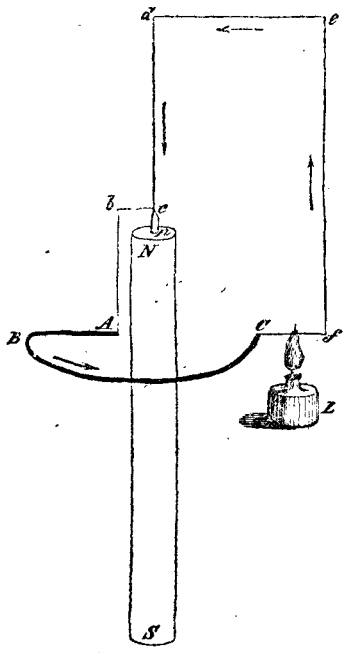


Fig. 273.

Relation between Thermo-electricity and the Molecular Structure of Bodies.

The influence, exercised by the molecular structure of bodies over thermo-electric phenomena, follows already from the fact, that one of the conditions essential for the development of thermo-electricity, is that the heated body shall be solid. Thus, M. Matteucci succeeded in demonstrating that the contact of hot mercury with cold mercury produces no thermo-electric current; that, consequently, contrary to the opinion of many philosophers, mercury cannot become thermo-electric. He had at first obtained this negative

result, by having three consecutive capsules filled with mercury connected by two syphons, filled also with the same liquid. The two extremes were made to communicate with the ends of the wire of the galvanometer; then, after having removed one of the syphons, the mercury of the intermediate capsule alone is heated; the syphon, filled with mercury, is immediately replaced, and a contact is thus established between a large mass of heated mercury and the cold mercury of the syphon, without the galvanometer detecting any current, excepting a few very irregular and slight movements of the needle, which arise from the heating of one or other of the two wires of the galvanometer by the effect of the passage of heated mercury, which always more or less takes place to one or other of the two extreme capsules.

Certain objections having been raised against this process by M. Vorsselmann de Heer and by M. Peltier, M. Matteucci adopted another method, which led him to the same result. It consists in taking an earthen crucible, at the bottom of which are cemented two bent glass tubes; the crucible is separated into two compartments by a diaphragm, formed of a slice of wood, which slides into a groove, and which consequently may be removed at pleasure. The two tubes are, in the outset, filled with mercury, and the two ends of the galvanometer are plunged into them. Then, into one of the compartments is poured mercury cooled down to 14°, and into the other mercury at 356°. The diaphragm is then removed, by sliding it out of the groove. An immediate contact is thus brought about between the hot and the cold mercury, exactly as Nobili and Becquerel had operated to show the production of thermo-electric currents with wires, and yet no deviation of the needle is obtained, although the galvanometer is constructed, so as to be as sensible as possible of thermo-electric currents.

What has led several physicists to think that mercury might give thermo-electric currents is, that it is a very difficult matter to avoid the contact of the heated mercury with the wires of the galvanometer. But nothing more is necessary, as M. Matteucci has demonstrated, than to plunge two homo-

geneous, as well as heterogeneous wires into two masses of mercury, which communicate together by means of a syphon, filled with mercury, and of which one is hot and the other cold, in order to obtain a thermo-electric current, which goes from the hot to the cold metal in the wire of the galvanometer, with the greater part of the metals, such as antimony, platinum, copper, zinc, iron, and even with carbon; bismuth alone forms an exception. If the surfaces of the metal are well polished, a current is obtained, that goes from the cold to the hot bismuth, instead of going, as with the others, from the hot to the cold, whatever may be the difference of the temperature of the two masses of mercury. Bismuth gives a current, that goes, on the contrary, from the hot metal to the cold if, instead of establishing the circuit through the mercury, the metal, heated at the spirit-lamp, is placed upon the metal, that remained cold; antimony and platinum, on their part, give in this case a current that goes from the cold to the hot, instead of travelling from the hot to the cold, as when they were immersed in mercury. Copper, zinc, iron, and carbon, do not change, at least when they do not suffer any alteration by the action of the air; for, if the copper is oxidised, the direction of the current is reversed, even when the circuit is established through mercury. Iron, although oxidised, does not vary in the direction of the current, that it produces.

M. Gaugain, in some recent experiments, has confirmed, in part, and modified in certain points, the results obtained by M. Matteucci. He operated very simply by placing the two wires, submitted to experiment, in relation with a galvanometer; he connected their free ends, by placing them one upon the other; he then heated in turn each of the wires, by means of a spirit-lamp, placed near the point of junction; and he observed the direction of deviation, corresponding to each of the two positions of the source of heat. The wires in these experiments were all about $\frac{1}{25}$ of an inch in diameter, and were annealed. With wires of copper, and of iron, the current travels from the cold wire to the hot one, if the surfaces of contact are very metallic. If these surfaces are oxidised or carbonated, the current goes from the hot wire

to the cold. With silver and with zinc wires, the results are the reverse.

On operating upon circuits formed of two wires of a different nature, M. Gaugain found a very much greater number still of irregularities. The duration of the current depends not only upon the fact that the two wires have between them a metallic contact, or that they be separated by a film of oxide or of carburet; but also on the absolute temperature, to which they are exposed. This current varies even according as, in the case of metallic contact, the wires are strongly pressed one against the other, or only touch each other lightly; it is clear that the change, when it takes place in this latter case, is due to there being formed, by the effect of the heat, a slight film of oxide upon the surface of contact of one of the metals. Thus all the phenomena enters into the two categories; either immediate metallic contact, or a film either of oxide or of carburet, interposed between the two metals. Then, instead of a single pair, we have two forms of it,—the former of one of the metals and of the film of oxide, the latter of the same film of oxide and of the other metal; and the effect observed is only the difference of the effects due to each pair separately. In support of this explanation, M. Gaugain quotes the fact of a thin plate of platinum, which, being interposed between two silver wires, changes the direction of the current, which travels from the cold to the hot, instead of travelling from the hot to the cold, as had taken place, when the two silver wires were in immediate contact.

M. Gaugain's experiments, like those of M. Matteucci, show to us that thermo-electric phenomena are less simple than MM. Becquerel and Nobili had supposed. The researches of Yelin and of Sturgeon had already proved the very great influence that is exercised over the result, by the molecular state of the body, in which the heat is propagated. Thus Sturgeon had found, on making frames or rings of bismuth and antimony, that there are, in these frames, points which, when heated, produce currents; and others, which develope none. He had called these *neutral points*. These

points have this characteristic, that, if the metal on their right is heated, a current is obtained in the opposite direction to that, which is obtained when it is heated to their left. M. Matteucci satisfied himself that the neutral point is found as well for antimony as for bismuth, in the portion of one of the sides of the frame, which corresponds to the point by which the metal had run into the mould, whereby its form was given to it; which seem to indicate that the corresponding section is, as it were, the surface of contact of the two portions of the frame, that it separates. With regard to the absolute direction of the current, it travels in the bismuth from the cold to the hot part through the section of contact; and, in antimony, it follows a converse direction. When the frame of bismuth, or of antimony, is allowed to cool slowly in the mould, neutral points are obtained, wherever there is a boss, namely, wherever the inferior liquid matter has raised up the crust. M. Matteucci, who has made a great number of researches upon this subject, adds the important remark, that the matter, in all the neutral points, presents a crystallisation different from that of the rest of the metal.

We shall not dwell upon M. Vorsselmann de Heer's experiments, who, by operating with bismuth and with antimony, has seen the current go, in the same metal, sometimes from the hot to the cold metal, sometimes from the cold to the hot; variations which he thought he might attribute to the greater or less differences of temperature between the two bars placed in contact. All these irregularities are due to the crystalline state of the substances, as has been demonstrated successively by M. Svanberg, M. Frantz, and M. Matteucci himself.

M. Svanberg, following up Faraday's researches upon the magneto-crystalline power of bismuth and of antimony, and the observation of this philosopher upon the existence in these crystals of a plane of cleavage, endowed with greater brilliancy than the others, procured bars of bismuth and of antimony, some of which had their length, perpendicular to this plane of cleavage, like Faraday's magno-crystallic axis*;

* Vol. I. p. 484.

whilst the length of the others coincided with the intersection of this plane of cleavage, endowed with the greatest brilliancy, and of another, whose brilliancy does not greatly yield to that of the former. The former bars are more negative and the latter more positive in the thermo-electric series, than any other bar that might be formed of the same metal. M. Svanberg has made the important remark, that, for antimony, as well as for bismuth, if the two bars placed in contact are those whose length is perpendicular to the plane of principal cleavage, the current goes from the cold metal to the hot, whilst if they are those whose length is parallel to the intersection of the two planes of cleavage, the current goes from the cold metal to the hot. No inversion of current is obtained, on moving the difference of temperature between the two extremities placed in contact. It follows, therefore, from this, that the differences observed, with regard to the direction of the current, and the changes that this deviation frequently undergoes, are due in bismuth and in antimony to their crystalline state, and to the position of the planes of cleavage of the specimen submitted to experiment, in relation to the point of contact of the hot and the cold metal.

M. Frantz has studied the influence of the position of the principal plane of cleavage on the thermo-electric powers of cubical specimens of bismuth and antimony. These specimens of the volume of about ·06 cub. in., were so cut, that in each the direction of the principal plane of cleavage was either parallel to two of the faces, or formed an angle of 30° with one of the faces, and consequently of 60° with the other. By this means, two cubes may be placed, one against the other, so that their planes of cleavage are parallel, or are inclined in respect to each other, 30° or 60°. In order to operate, M. Frantz placed the cubes between plates of polished glass firmly fixed; and he made them communicate with the wires of the multiplier by means of small columns of copper, in the form of a square prism. A cylinder of glass, that has been heated in a sand-bath, is placed exactly on the line of contact of the cubes submitted to experiment, which enables us to heat this line to a constant temperature, and one easy of

measurements. By means of a lever, suitably arranged, which is loaded with weights, in greater or less amount, the cubes are pressed against each other, so as to render their contact more intimate. The pressure, in M. Frantz's experiments, was generally 16½ lbs.

The two cubes, placed between the columns of copper, were first two cubes of bismuth; they were so arranged that their planes of cleavage had a uniform and vertical direction, perpendicular to the line, that joins the two columns of copper between which they were placed. On heating their line of contact, no current is developed, except certain slight irregular currents, due to the perfect non-homogeneity of the internal structure of the metal. If we place cubes, so cut, that the plane of cleavage is inclined 30° to the horizon, a current is obtained of 34° 5′ on heating their line of contact; if the plane of cleavage is inclined 60°, the deviation is not more than 19° 7′; the deviations are exactly of the same value, but in a contrary direction, when the plane of cleavage is lowered in a similar manner, toward the second column of copper instead of being so toward the first. Finally, if the cubes are so placed, that in both the principal plane of cleavage forms the same angle with the vertical plane, there is no current. Neither is there any when the principal planes of cleavage, being placed in an axial direction, form together an angle of 90°; but a mean deviation of 45° is obtained, when the cubes are placed one against the other, so that the principal plane of cleavage of one is in an axial position, and that of the other in an equatorial position.

It follows, from M. Frantz's experiments, that, in every piece of bismuth, cut in the same manner, the inclination of the plane of cleavage indicates the direction of the positive current, developed by the heating of the metal; and that, when we heat the place of contact of two different pieces, whose principal planes of cleavage are inclined one in respect to the other, there is developed a current, that always goes from the direction which is equatorial for this current, and with the more facility, in proportion as the angle, formed by the principal planes of cleavage, is greater.

Antimony, which also possesses a principal plane of cleavage

altogether predominant, presents the same phenomena as bismuth. On pressing against each other two cubes of antimony, so that their principal planes of cleavage are in the same position, no current is obtained, when their surface of contact is heated up to 212°; but a deviation of 12° 4′ is brought about on arranging the cubes, so that the plane of cleavage of one is in an axial position, and that of the other in an equatorial. In this case, the current also travels from the cube, whose plane of cleavage occupies the equatorial position in respect to the surface of contact to that, whose plane of cleavage occupies the axial position.

If cubes made of various other metals are successively placed in contact, either with the cube of bismuth, or with that of antimony, thermo-electric currents are obtained, whose intensity presents considerable differences, according as the plane of cleavage of the bismuth or of the antimony is placed axially or equatorially, in respect to the surface of contact, which is always the heated part. The current is twice as strong with equatorial bismuth as with axial bismuth, when combined with iron, lead, zinc, German silver, brass, silver, copper, and tin; it is the reverse when antimony is substituted for bismuth. The only exception is that presented by steel. With this metal, the current is more powerful when the bismuth is axial, than when it is equatorial; with antimony, steel comports itself like the other metals. We must not forget that, in the combinations of bismuth with the other metals, the current goes from the bismuth to the metal, through the heated surface of contact, whilst it goes from the metal to the antimony, when this latter is substituted for the bismuth.

The following, moreover, is the order, in which the metallic cubes, submitted to experiment, may be ranged so that each gives, for a temperature of 212°, a positive current with the following: *bismuth* (plane of cleavage equatorial), *German silver, brass, tin, copper, silver, zinc, lead, steel, iron, antimony* (plane of cleavage equatorial), *antimony* (plane of cleavage axial).

M. Matteucci has lately verified the experiments of MM. Svanberg and Frantz, in a complete manner. He procured

tolerably long rods of bismuth, having throughout their length the cleavage parallel or perpendicular to the length, by allowing a stratum of pure bismuth from $\frac{3}{4}$ inch to 1 inch in thickness, to cool very slowly in a large earthen plate; he called the former *equatorial*, and the latter *axial*, founded upon the position of equilibrium, assumed by the rods between the poles of an electro-magnet, and which very well manifests their uniform structure. He found that, with two axial rods, the thermo-electric current is directed from the heated rod to the other in the surface of contact, and that with the equatorial rods the current has an opposite direction. On heating the line of contact of an axial rod and an equatorial rod, a thermo-electric current is obtained, which goes from the former to the latter at the surface of contact. In order to facilitate the experiments, it is necessary to take two cubes of crystallised bismuth, whose two faces are parallel to the principal plane of cleavage. These two cubes are held in contact, by being pressed between two copper rods, which screw horizontally and which lead to the galvanometer; it is essential to take care to maintain the contact between the rods and the cubes at a constant temperature, and to raise the temperature of the line of contact of the two cubes, by touching it with a rod of heated glass. In order to obtain the results described, nothing more is necessary than to make each cube perform quarters of a revolution.

It is evident that the influence of the planes of cleavage in these phenomena is due, as in those of diamagnetism and in many others, to the molecules being nearer, in the direction of these planes, than in a direction perpendicular; and the proof is that Matteucci has succeeded in developing by compression in bismuth thermo-electric properties, similar to those, which crystallisation imparts to this metal. The same philosopher has observed that compression is in like manner able to bring about in bismuth differences of conductibility, as well for electricity as for heat, analogous to those, which result from the natural arrangement of the planes of cleavage. Thus equatorial rods of bismuth conduct electricity and heat better than do axial rods; in like manner, the conductibility

for electricity and for heat is greater parallel to the direction, according to which the bismuth has been compressed, than perpendicularly to this direction.

M. Matteucci, in order to demonstrate the influence of molecular structure over thermo-electric phenomena, satisfied himself, as he had done for mercury, that there is no thermo-electric current developed in the contact of melted bismuth with a layer of bismuth also melted, but more heated than the former. Yet, of two columns of the same length and the same diameter, one of melted bismuth, the other of solid, the former conducts electricity better than the latter; it is not therefore to the differences of electric conductibility that the production of thermo-electricity is due.

It there follows, therefore, from all the facts, that we have been enumerating, the demonstration of the very great influence, that is exercised over thermo-electric phenomena, by the molecular constitution of bodies. This influence had already been proved in 1844 by M. Mousson, in a series of experiments, by which he had demonstrated that, in a homogeneous wire, the slightest difference in the molecular equilibrium of its different parts, is sufficient to bring about a current, by the application of heat to one of its points; whilst when the wire is in a perfect state of molecular homogeneity, no current is developed by heating any single point whatever, providing this state of homogeneity is not destroyed by the very application of heat, as takes place with an unannealed wire, and not with one already annealed. The current, that follows from the differences in the molecular state, varies in direction and in intensity with the different metals. In copper and in iron, it goes from the parts that are the more elastic, to those which are the more ductile; in brass, the reverse is the case. M. Mousson, independently of these general results, had recognised that other circumstances, difficult of determination, exert an influence over the direction and the intensity of the current.

M. Magnus has latterly taken up this same question; and he has arrived at results, that appear to us to determine in a very precise manner, the nature of thermo-electric phenomena, and their intimate connection with molecular changes.

Only, in order not to alter the molecular state of the wire, no higher temperature must be employed than 212° for heating it; and care must be taken that the two portions, where it is in communication with the galvanometer, shall have exactly the same temperature.

The first point to be established is to learn whether the development of the current, that results in a homogeneous wire, from an increase of volume arising from a knot, as M. Becquerel was the first to obtain, or from an increase of diameter in a portion of the length of the wire, is due to the difference of the propagation of heat that takes place, when the wire is heated near to the point, or at the point itself, where its volume changes, or to an alteration in its molecular state, produced by the act that has brought about this change of volume. Many experiments have demonstrated that it was to this latter cause, and not to the former, that the production of the current must be attributed; we will quote the following, which appears to us the most direct and the most demonstrative. A thick brass wire a yard in length, and nearly $\frac{1}{4}$ in. in diameter (*fig.* 274.), was made thin near to its

Fig. 274.

middle, so as along a length of 6 in. to preserve a diameter of only $\frac{1}{25}$ of an inch. On heating one of the points, where the diameter varied suddenly, there was no current. This important experiment, varied in many ways, always gave the same negative result. On the other hand, if a very thin film of copper is deposited by the voltaic process upon a German silver wire, the wire, when heated at the point, where the film of copper terminates, developes a very strong current. An analogous effect is produced by a thin film of oxide, when it covers the surface of a metal. It is not to a modification in the radiating power of the metal, that the effect of these films may be attributed; for, on modifying this power directly by the superposition of non-conducting films, the same result is not obtained.

Thus, it appears well proved, that in a homogeneous metal, it is not from an inequality in the quantities of heat propagated in the two contrary directions, setting out from the heated part, that the production of the thermo-electric current depends; since the difference of volumes is not sufficient of itself alone to generate these currents; but that a difference in the molecular state is essentially necessary, as well, when the volumes are different, as when they are equal. M. Magnus further satisfied himself that unannealing or annealing does not sensibly modify the internal conductibility of a large wire of brass or of German silver; and that consequently the thermo-electric currents, which are developed in a wire, of which one part is annealed and the other not, cannot be attributed to an inequality in the quantity of heat propagated in one of its parts and in the other.

Now, the following are the results obtained by M. Magnus upon wires drawn out to $\frac{1}{25}$ of an inch in diameter and 6 ft. in length, and annealed on a length of only $25\frac{1}{2}$ in. raising each of them to the temperature of 212° at the point of separation of the annealed and the unannealed portion. In the following Table, the direction of the current is indicated as going from one part of the wire to the other, through the heated point.

Metal.	Direction of the Current.	Deviation.
Brass - - -	From the annealed to the unannealed part.	55°
Silver* -	Id.	46
Steel - - -	Id.	
Silver at 750° of fineness - -	Id.	45
Cadmium - -	Id.	40
Copper - -	Id.	25
Gold, No. 1.† -	Id.	18
Platinum - -	Id.	10
Gold, No. 2.‡ -	Id.	5
German silver -	From the unannealed to the annealed part.	2
Zinc - - -	Id.	34
Tin - - -	Id.	32
Iron - - -	Id.	30
Lead - - -	Doubtful.	4
		0

* Containing 0·0087 of copper.
† Containing 0·0097 of copper, and prepared with Prussian gold Fredericks.
‡ Containing 0·0011 of silver and prepared with Dutch ducats.

The effects may be increased in the following manner: an unannealed wire is taken, and various portions of it, equal in respect to each other, and separated by equal portions, are annealed; it is wound upon a frame, the circumference of which is equal to double the length of an annealed part, so that the points of separation of the annealed and the unannealed parts, are found alternately on the two opposite sides of the frame. On heating all the points, situated on the same side, currents are brought about in the same direction, which are all added together. The experiment may be arranged, for example, as in *fig.* 275.

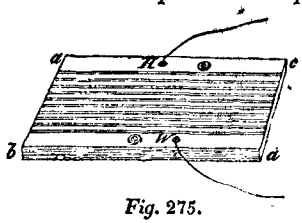


Fig. 275.

Finally, M. Magnus has further endeavoured to determine the direction and the intensity of the current, produced by the contact of two wires of the same nature, perfectly homogeneous, but raised to unequal temperatures, 46° and 212°, and then 46° and 482°, for certain wires only. In the experiments, the wires were either both unannealed or both annealed, or one annealed and the other unannealed. With wires of German silver, fine silver, copper, and tin, the current goes from the cold metal to the hot, by the surface of contact, whether they are both unannealed or annealed; it goes from the hot to the cold with wires of zinc, platinum, gold, cadmium, brass, and silver of the standard of 0·750. When one of the wires is unannealed and the other annealed, the direction of the currrent is very variable with the nature of the metals. Iron and steel do not give constant results in this mode of experimenting.

The apparatus, by means of which the operations are conducted, is a cylindrical vessel of tinned iron 4 in. in height and $2\frac{1}{4}$ in. in diameter (*fig.* 276.). At an inch above the bottom are four openings *a*, *b*, *c*, and *d*, through which pass four horizontal tubes, penetrating into the interior, as far as a vertical tube *g*. One of the wires, submitted to experiment, is stretched along the axis of the tubes *a* and *b*; as soon as the wire is heated to 212°, by means of a lamp, which

brings to this temperature the water, with which the vessel is filled, the second wire is stretched in the axis of the tubes *c* and *d*; then, by means of a cylinder of wood, movable with gentle friction, in the vertical tube *g*, the two wires are pressed against a piece of wood *f*, fixed below their point of crossing in the tube *g*. In order that the pressure may be the same in all the experiments, it is produced by means of a leaden weight *p*, placed above the wooden cylinder.

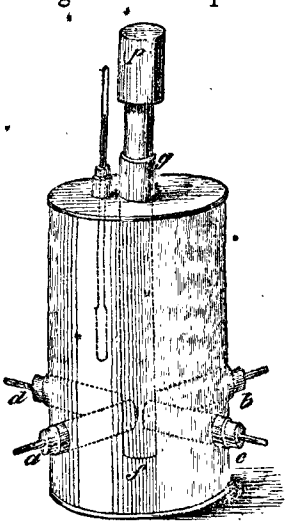


Fig. 276.

In order to operate at a temperature of 482°, a slightly different apparatus was employed. We may further add, that M. Magnus has entirely confirmed the result already obtained by M. Matteucci, namely, that no current is developed in the contact of hot mercury and cold. The following is his mode of operating. Two glass tubes A C, and B D, of the form represented in *fig.* 277., were filled with mercury; the extremities A and B of the two masses of mercury, were placed in communication with the galvanometer, by platinum wires, which traversed cork plugs, that were thrust in, as far as the surface of the mercury. The mercury of the enlargement C being heated, the drawn-out extremity D of the tube B D, retained at the ordinary temperature, was thrust into it. In another experiment, the extremity D was heated, and it

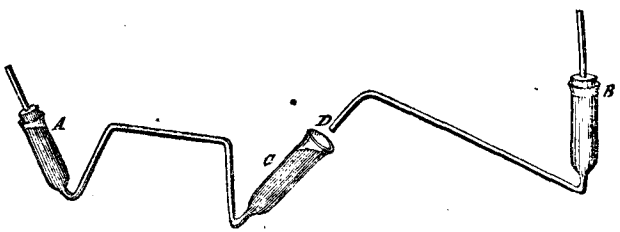


Fig. 277.

was plunged into the mass C, that remained cold; there was no trace of current. The columns of mercury in other respects had remained perfectly continuous, since they allowed the thermo-electric current, developed in the other parts of the circuit, to circulate.

To sum up: it appears to us now to be well established that, in thermo-electric phenomena, the cause of the currents exists, not in the fact itself of the propagation of the heat, but in the molecular effects, that accompany this propagation. Also, when the two portions of a body are perfectly homogeneous, to the left and to the right of the heated point, the molecular effects, produced by this heat being identical, two currents are the result, which, being called upon to traverse the same circuit, must be equal at the same time that they are contrary; but the slightest difference in the chemical nature, or in the molecular constitution of these two portions, brings about an intensity, greater in one of the currents than in the other, and consequently produces an effect, that is detected by the galvanometer. With regard to the relation, which M. Becquerel thought he had discovered between the thermo-electric power of metals and their radiating power for heat, it may be applied up to a certain point, in considering that these two powers are equally connected with the molecular state of bodies, as we proved for the former power, and as M. Melloni did for the latter.

We shall endeavour, further on, and when we shall have been more advanced in the study of the sources of electricity, to see how the connection may be explained, that exists between the production of electricity and the molecular effects, that accompany the propagation of heat.

Thermo-electric Piles and application of Thermo-electricity to the Measurement of Temperatures.

A short time after Seebeck's discovery, Fourrier and Œrsted conceived the idea of connecting several thermo-electric pairs, by soldering alternately together, a series of bars of bismuth and antimony, and heating the alternate

solderings, so as always to leave one cold between two hot ones. A magnetised needle, placed simply upon one of the bars of this circuit, to which a polygonal form had been given, experienced a decided deviation. The same result is obtained by maintaining the alternate solderings at 32°, by means of melting ice, those which are not cooling, to be considered as if heated, in respect to the others. The effect upon the needle is very considerable, when cooling and heating are combined; namely, when all the even solderings, for instance, are surrounded with melting ice, and all the odd ones are heated with a spirit-lamp. The two learned philosophers increased the number of their alternate bars of bismuth and antimony, so as to have as many as twenty-two of each kind. They remarked, that the total effect, exercised upon the needle by this compound circuit, is much inferior to the sum of the isolated effects, that is exerted by each of the simple circuits, of which it is formed; but if, *without changing the length of the compound circuit*, only a portion of the pairs are put into a state of activity, by not heating or cooling all the alternate solderings, then a less effect is obtained: and we are enabled to discover that the intensity of the current is proportional to the number of the elements, that are in action. On the other hand, with perfectly similar pairs, placed under the same conditions of temperature, and confined so as to form piles of eight and sixteen and of thirty-two elements, currents of the same intensity are obtained, whatever be the number of the pairs of the pile. A single pair produces, in like manner, a current of the same intensity. It follows from this, that in a pile of sixteen pairs, the current of each pair is only the sixteenth part of that, which each of the pairs taken separately would produce; and that, if only a single pair of this pile is put into action, the current of the pile is only the sixteenth of that which would be developed by this pair isolated, when it should be forming a circuit of itself alone.

These results, already pointed out by Fourrier and M. Œrsted, have been confirmed and perfectly well explained by M. Pouillet, as the result of researches as accurate as they were ample. They come in support of the laws that we have

already established in the First Chapter of the Fourth Part *, upon the intensity of currents in closed circuits; and, in particular, of this fundamental law, that *the intensity of a current is in inverse ratio of the length of the circuit that it traverses.* And, in effect, if, on the other hand, in a thermo-electric pile, the intensity of the current is proportional to the number of pairs put into action, and that, on the other hand, this same intensity is inversely as the length of the circuit, and consequently of the same number of pairs, it must follow, that whatever be their number, provided the pairs be perfectly identical, and form a circuit completely closed, without the intervention of any other conductors, the force of the current will be independent of the number of pairs.

It was by actually employing thermo-electric currents that M. Pouillet succeeded in establishing the general laws, which regulate the propagation of electric currents in good conductors; laws, which Ohm and Fechner, on their part, had discovered by employing ordinary voltaic or hydro-electric currents. Thermo-electric currents have the advantage, for this class of researches, of being more regular and more constant, and of requiring for their development only a circuit, that is perfectly metallic, and consequently not exposed to the disturbances that are introduced by the alternation of solid and liquid conductors; but they present the inconvenience of having a very limited intensity.

In order to get at the laws relating to the influence exerted over the intensity of the current, by the length and the section of the circuit, M. Pouillet employed two pairs, perfectly similar, and each formed by a cylinder of bismuth (*figs.* 278, and 279.), at the two extremities of which is soldered a copper wire of about a yard in length; one of the solderings of each pair was maintained at 32°, and the other at 212°; then their circuit was closed by wires of any kind. We are thus able to prove, by means of a differential galvanometer, whose two wires are traversed in contrary directions, by the currents of these two pairs, that these currents are perfectly equal.

* Vol. II. p. 65.

Then, in order to demonstrate that their intensity is in inverse ratio to the length of the circuit, two similar wires are taken

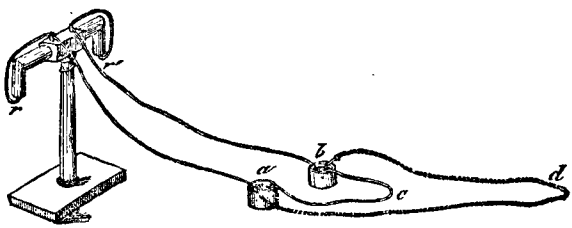


Fig. 278.

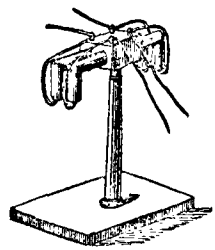


Fig. 279.

in order to form the circuits of the two pairs; but, for one of the pairs, the wire is only 8 yds. in length, whilst for the other it is 98 yds.; which gives for the former a total length of 10 yds. and one of 100 yds. for the latter. With the circuit of 10 yds. two turns are made upon the frame of the multiplier, and twenty turns with that of 100 yds.; then, on making the currents pass in the reverse direction, the needle remains motionless. Therefore the current of the circuit ten times longer is ten times weaker; since it is necessary for it to act, by a number of turns ten times greater, in order to compensate the effect of the current of the circuit, that is ten times shorter. It is by a similar process that Pouillet has proved that the intensity is proportional to the section, either by closing one of the circuits by three or four similar wires, or by taking a thicker wire, one portion of which has been drawn into a fine wire, in order to be quite sure of the homogeneity of the metal, or by laminating a wire, in order to show that the extent of the surface has no influence, provided that the volume remains the same. In these experiments, the resistance of the bismuth bar may be neglected, on account of the great diameter and the small length of this bar, compared with the diameter and the length of the copper wire.

The laws to which we have just directed attention, joined to others that we have established in the First Chapter of the Fourth Part, enable us to determine the arrangement, that is most suitable to give to a multiplier, in order that it shall

have the greatest sensibility in measuring thermo-electric currents. All depends upon the length, and consequently upon the resistance, possessed by the thermo-electric circuit. Suppose, for example, that it is equal to that of a copper wire 100 yds. in length and $\frac{1}{250}$ in. in diameter, if we place in the circuit a multiplier, the wire of which has this length and this diameter, we reduce the intensity of the current one-half, but we have around the frame of the multiplier a very great number of turns, which will be very near together and which will act powerfully upon the needles. If a length of only 10 yds. is given to the wire, the intensity of the current will be reduced to only $\frac{10}{11}$ of its primitive intensity, instead of being reduced to the half; but also with the 10 yds. ten times fewer turns will be made than with the 100; and it is evident that 100 turns, each of which acts with an intensity of half, will produce upon the needles much more effect than ten, each of which acts with an intensity of $\frac{10}{11}$; in the former case the intensity is 50, in the latter $\frac{100}{11}$, or about 9. If the wire of the galvanometer multiplier was larger, still remaining of the same length, if for example it was $\frac{1}{25}$ in. in diameter, its interposition in the circuit would cause almost no change in the intensity of the current, as may be easily perceived; also a much more considerable effect upon the needles would be the result; but, however, it is necessary to observe that, although the number of turns remains the same, the greater thickness of the wire causes them to be more distant from the needles, and to act consequently less powerfully upon them. It is important, therefore, in the construction of the galvanometer multiplier, intended for the measuring of thermo-electric currents, carefully to estimate these various elements, and to know how to turn them to account. In general, the wires of these galvanometers ought to be thick and short, especially when the current has itself very little length, and presents consequently very little resistance to the current. We may add that, if it is in our power to reduce the length of the circuit at our pleasure, the multiplier no longer multiplies; for, supposing that the resistance of the thermo-electric pair may be neglected, it is evident that, with a wire of a nature and di-

ameter, so arranged, as to have ten turns on the multiplier, it is necessary to give to the wire a tenfold length, which reduces the intensity to its tenth part; so that we lose as much as we gain, since a single turn would have ten times more power than each of the ten. Thus, more effect is obtained with the antimony and bismuth pair of *fig.* 266., by making it act directly upon the magnetised needle, than by interposing in its circuit a galvanometer multiplier.

We may easily conceive, from what has gone before, that the interposition in the thermo-electric current of conductors, that present a very great resistance to the current, such as very fine wires, liquids or the human body must singularly enfeeble this current. Also, in order to produce with a pile some of the effects, that require a very great electric tension, such as chemical effects, for example, we are obliged to increase the resistance of the pile itself, by constructing it of a very great number of pairs, and by employing, in order to form these pairs, metals, that are as bad conductors as possible. By increasing the number of pairs, we do not increase the force of the current, as we have seen, but we greatly diminish the weakening that this current will undergo by the interposition in the circuit of an imperfect conductor. It was by this means that Botto has succeeded in decomposing water slightly acidulated, by the current of a thermo-electric pile, formed of 120 pieces of platinum wire each an inch in length, and $\frac{1}{100}$ in. in diameter, alternating with an equal number of pieces of soft iron of the same dimensions. The chain formed by the succession of these 240 pieces of wire, was coiled round a wooden ruler about 20 in. in length; so that the odd points of contact were on one side of the ruler and the even on the other side, at about $\frac{2}{3}$ in. distance from the former, which were heated with a spirit-lamp of the same length as the ruler.

M. Poggendorff has also contrived a thermo-electric combination, which cannot, it is true, be subjected to so elevated a temperature as that of the iron and platinum, but which is nevertheless almost as efficacious, at the same time that it is much more economical; he obtains it, by substituting for pla-

tinum German silver, which is a metal eminently positive in the thermo-electric series; for it immediately follows bismuth, and goes before platinum. At equal temperatures and for the same number of pairs, the German silver and iron pile has a greater electro-motive force than the platinum and iron pile; as Poggendorff has proved by a direct comparison, made by means of a differential galvanometer. In this pile, the wires may be arranged, one after the other, along a right

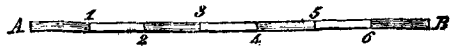


Fig. 280.

line (*fig.* 280.), or disposed in a zigzag (*fig.* 281.), or even in a cluster (*fig.* 282.), in order that a change of temperature

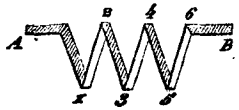


Fig. 281.

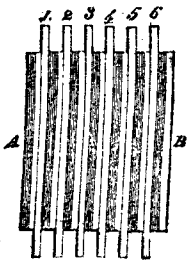


Fig. 282.

may more easily be effected between the even and the odd points of contact. In all these figures, the shaded lines indicate the German silver wires, and the plain lines the iron wires. The tension of the electricity, at the two extremities of this pile, increases with the number of pairs and with the difference of temperature, that is established between the even and odd solderings. Kohlrausch constructed one formed of 769 pairs, and consequently presenting 769 odd points of contact, and the same number of even. Each pair was formed of an iron wire about $2\frac{1}{4}$ in. in length, and $\frac{1}{50}$ in. in diameter, and of a narrow band of German silver; the solderings were made with tin; the pairs were fixed in wax, and small bands of wood served to maintain them in a suitable position. The pile was terminated, at its two

extremities, by iron wires situated in the upper part of the cluster, upon which might be adjusted a dish, filled with melting ice or snow, whilst the lower part was tightly enclosed in a box of cast-iron, that was plunged into water. When placed in communication with the condenser, by one or other of its extremities, the pile does not become charged until the water has been heated by a spirit-lamp; positive electricity is then obtained at the extremity B, the odd points of soldering being those that were heated, and negative at the extremity A. Precise measure, taken by means of the electric balance, showed that the electric tension of each of the poles, increasing with the number of pairs, was 0·79 with 349, 1·18 with 420, and 1·97 with 769.

With a thermo-electric pile of bars of bismuth and antimony, constructed in the same manner, but in which there were only twenty pairs, and the bars of which are three or four inches in length by about $\frac{1}{5}$ in. in diameter, currents are obtained, which are very suitable for producing effects of induction; and can give powerful sparks, when made to pass through a thick wire or a metallic ribbon, coiled into a spiral. Only it is necessary, in order to produce greater effects, to substitute for the hot water a plate of sheet-iron, which is heated by the lamp.

The thermo-electric pile, as may be imagined from the description we have given of it, is not an instrument of a nature to be very useful for the production of electric currents, except in certain particular cases, in which we are more concerned in studying the effects of dynamic electricity, than in determining the laws of its propagation. But it may render to science services of another kind, in furnishing it with a more sensitive means, than any other that is known, of appreciating differences of temperature. For this important application of thermo-electricity, we are indebted to M. Nobili. He first constructed a thermo-electric pile, formed of six pairs of bismuth and antimony, arranged in crowns, and placed in the interior of a cylindrical box, so that the odd points of contact were in the upper part, and the even, being placed below, were concealed at the bottom of the

box, and surrounded with a bed of mastic, rising to about a quarter of an inch only below the odd points of contact. The extremities of the pile were soldered to two attached pieces of copper, which, coming out of the box, served to put the pile in communication with the extremities of a galvanometer-multiplier having two needles. M. Nobili, having placed the thermo-electric box under a receiver of the air-pump, on rarefying the air, obtained a cooling, which, being felt immediately at the upper points of contact not surrounded with mastic, produced a very decided current; he was thus able to assure himself that the sensibility of his thermo-multiplier was fifteen or twenty times greater than that of Breguet's metallic thermometers. Various improvements were introduced by MM. Nobili and Melloni into the original apparatus of the former; and these two philosophers succeeded, by means of their thermo-multiplier, in discovering the presence of heat in insects, in phosphorescent bodies, in a word, in a great number of cases, in which we had not previously been able to suspect it. But it is essentially to Melloni, that we are indebted, by the precautions he has introduced into the construction of the thermo-electric pile, for having made it one of the most valuable instruments of experimental physics.

M. Melloni's pile is composed of fifty small and very slender bars of bismuth and antimony, of about $1\frac{1}{2}$ or 2 in. in length, soldered one to the other, so that the bars of bismuth alternated with those of antimony, as represented in *fig.* 283., and so arranged as to form a small, solid, and compact cluster (*fig.* 284.), by means of insulating mastic, that filled the vacan-

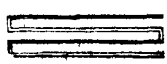


Fig. 283.

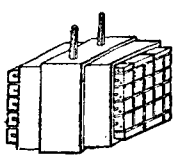


Fig. 284.

cies, left between themselves by the bars, which must touch only at the solderings. The two extreme bars of the

chain, one of bismuth, the other of antimony, communicate, by means of two copper wires, rather large, but very short, one at the stud x, and the other at the stud y, which thus form the two poles of the pile, that are placed in communication with the two extremities of the wire of a multiplier. The two studs pass through a piece of ivory, fixed upon a metal ring, which embraces the thermo-electric pile, and may, by means of a piece attached, furnished with a hinge allow of the axis of the pile to be placed in all desired directions. Care must be taken to blacken the terminal faces of the pile; and we must cover with a well-polished metal shield, which envelopes, without touching it, the face, that we desire to retain at an ambient temperature; whilst the other, being uncovered, is exposed to the sources of heat or of cold. The sensibility of this apparatus is such, that if the uncovered face of the pile is turned toward a person placed even at a distance of twenty-five feet, the deviation of the magnetised needle, detects the emanation of radiant caloric.

In order that the galvanometer-multiplier, adapted to the pile, should be as sensitive as possible, it would be necessary to know the length of wire of this galvanometer, equivalent in conductibility to the circuit itself of the pile, and to deduce from this the number of turns, necessary to be given to the instrument; but, by simple trials, Melloni succeeded in finding the galvanometer-multiplier, which best fulfilled the end. The copper wire, as pure as possible, is of a diameter of $\frac{1}{50}$ of an inch, and seven or eight yards in length; it makes forty convolutions around the frame; its coils are symmetrically arranged on one side, and the other of the mean line to a width of $1\frac{1}{2}$ in.; the needles, being well selected, and carefully magnetised and compensated, are connected together, by means of two fine copper wires, twisted together and delicately suspended to a filament from the cocoon. Thus constituted, the thermo-multiplier is of extreme sensibility, although at first sight it seems that the intervention of the wire of the galvanometer ought to diminish the intensity of the current; but this very slight diminution, in consequence of the smallness of the length and the size of the diameter of the

wire on the one hand, and the considerable number, as well as the small dimensions of the bars of bismuth and antimony on the other hand, is more than compensated, as we have already seen, by the increase of effect, that results from the number of turns, that act upon the magnetised needles. It is also to be remarked, that the very considerable number of thermo-electric pairs, of which the pile is composed, possesses the double advantage of enabling a greater surface to be presented to the action of the heat, and to render effective the intervention of the multiplier; the interposition of which, if there had been but a single pair, would have too much weakened the current.

In order to make use of the instrument in the measurement of temperatures, M. Melloni first proved, by a comparison with ordinary thermometers, that, with piles of bismuth and antimony, the intensity of the current is proportional to the difference of temperature of the solderings; then he succeeded, by causing the amount of heat to vary by a known quantity, in establishing the relation which connects the intensities of the current with the deviations of the needle, measured by means of a circular division, made with great care.* In M. Melloni's apparatus, the intensity is exactly proportional to the deviation, up to 20°; for more considerable deviations, a table of ten columns, drawn up empirically, gives the intensities corresponding to the deviations observed: but, in order to obtain more accuracy, we should endeavour, as M. Melloni succeeded in doing, not to obtain deviations, that sensibly surpass 30°.

M. Pouillet has also applied thermo-electricity to the measurement of temperatures, by constructing an instrument which, under the name of magnetic pyrometer, could measure all temperatures, from the greatest degree of cold, to the highest degree of heat. The instrument comprises two

* M. Melloni distinguishes the *impulsive deviation* and the *definitive deviation*; namely, the maximum distance, that the needle attains by its first motion of impulse, and the distance where it stops after a series of oscillations; he seized the constant relations, which exist between them, and which enable our deducing one from the other, when a table has been previously drawn up of these relations for each apparatus.

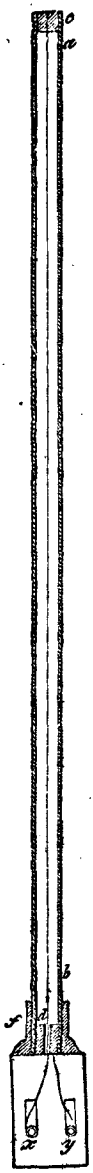


Fig. 285.

distinct pieces; namely, a galvanometer or sine-compass, formed with a copper ribbon about $\frac{3}{4}$ in. in length*, and the thermo-electric apparatus itself. This latter (*fig.* 285.) is composed of a tube of iron or rather of a gun-barrel *a b*, and of a platinum wire, that comes from the middle *c*, of the breech at the bottom, being incorporated with the mass of the iron; it traverses the axis of the tube, so as to arrive at the piece of copper *x*; from the annular breech *d*, proceeds a second platinum wire, which is soldered to the piece of copper; the second wire is maintained by a badly conducting body in the middle of the opening of the annular breech *d*, so that it cannot touch it; *f*, is a piece of wood, fixed upon the end of the tube, and intended to carry to the two pieces of copper *x* and *y*. The communication between the multiplier and the pyrometer properly so called is established by means of two copper wires of about $\frac{1}{25}$ of an inch in diameter, which abut on one side at the pieces *x* and *y* of the pyrometer, and on the other side at the extremities of the ribbon, of which the multiplier is composed.

M. Pouillet has graduated his instrument by comparison with an air pyrometer; but the intensity of the current is far from being proportional to the temperature; at least with the platinum and iron pair. It is not the same with a bismuth and copper pair; experiments made comparatively with an air pyrometer and an alcohol thermometer have shown that the intensity of the current of this pair, measured by the sine-galvanometer, is well proportional to the temperature, between 212° to — 108°·4. The low temperatures were obtained, by means of the paste of ether and carbonic acid, into which one of the solderings

* Vol. I. p. 335.

of the pair was plunged, whilst the other was in melting ice. The thermo-electric pyrometer gives −41° for the temperature of the coagulation of mercury, which agrees with the indications of the air thermometer.

The question of the relations that exist between the insensities of thermo-electric currents, and the corresponding temperatures, had been already discussed by M. Becquerel, as we have already seen in the paragraph commencing at p. 535.; nevertheless, notwithstanding these researches and those of M. Pouillet, there was something still to be desired, in regard to the confidence, that might be attached to the employment of the thermo-electric properties of metals, for the accurate measurement of temperature. This induced M. Regnault to study carefully, in his researches upon heat, this thermo-electric process, according to a method very different from those, which had been hitherto employed, and which led him to important results.

He first constructed a bismuth and antimony pair, formed of two bars A B C D (*fig.* 286.), obtained by casting, and

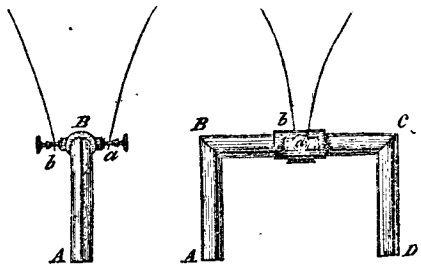


Fig. 286.

which, being perfectly similar, are juxtaposed in all their extent, being separated by a thin plate of ivory, which does not permit of their touching, except at the extremities A and D, where the two solderings are situated. The apparatus is divided, so that the wire of a galvanometer may be introduced into the circuit. This pair, the vertical branches of which are $4\frac{3}{4}$ in. in length, whilst the horizontal branch is $7\frac{3}{4}$ in., is the normal pair, to which all the other thermo-electric pairs must

be referred; but it must be employed only for rather low temperatures, which do not exceed 86°.

The pair, intended for high temperatures, is formed of an iron and a platinum wire $\frac{1}{25}$ of an inch in diameter, the extremities of which are soldered to silver; the iron wire E and F (*fig.* 287.), is about 31 in. in length; and the two platinum wires E *c*, and F *d*, are attached near to the iron wire from which they are separated by an insulating envelope; in the lower part, the wires are separated by a plate of thin glass; they are terminated by two pieces of brass attached, which allow of the galvanometric wire being introduced into the circuit.

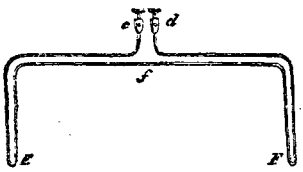


Fig. 287.

The galvanometer, that is employed is a very sensitive differential galvanometer, one of the wires of which is introduced into the bismuth and antimony circuit and the other into the iron and platinum circuit. The normal pair, bismuth and antimony, is so arranged, that the two solderings plunge into two vessels filled with water at different temperatures, and separated from each other by a screen; two thermometers, very accurate and rigorously compared, give the temperature, in which each of the solderings is placed. The solderings E and F, of the iron and platinum pairs, are maintained in glass tubes filled with fine oil, that does not contain any oxygen; one of the tubes is placed in a boiler full of oil with a mercury thermometer ranging from 32° to 662°; the other, which contains the second soldering, is maintained at a constant temperature, by means of melting ice, or in a large water bath, beside the mercury thermometer.

The apparatus being then arranged, if the soldering F, of the iron platinum pair, is raised to a temperature, measured by the thermometer, of the oil-bath, a current results, which deflects the needle of the galvanometer; but on raising to the necessary quantity, the temperature of one of the solderings of the bismuth and antimony pair, a second current is obtained, which, moving in a contrary direction to the former, neutralises its effects, and brings back the needle

to 0°. A note is made of the temperatures indicated by the two thermometers at the moments of neutralisation. The difference of temperature, that produces upon the bismuth and antimony pair a current, capable of neutralising that, which is produced by a certain difference of temperature upon the iron and platinum pair, is much less than this latter; for the latter being 212° the former is only 43°·7.

By raising the oil bath to different temperatures, currents are obtained in the iron and platinum pair which produce equilibrium on the galvanometer, with the currents produced in the bismuth and antimony pair, by corresponding differences of temperature. A table can therefore be drawn out in which are inscribed, on the one side, the differences of temperature $T' - T$, $T'' - T$, $T''' - T$, of the iron and platinum pair, measured by the air thermometer, and on the other the differences of temperature $t' - t$, $t'' - t$, $t''' - t$, of the bismuth and antimony pair. If we desire to measure an elevated temperature with the iron and platinum pair, we have merely to seek for the temperature, $t'' - t$, which produces equilibrium with it, and the bismuth and antimony pair, and in the table is found the corresponding temperature $T'' - T$, on the iron and platinum pair. It is necessary, in order that the results may be exact, that the two pairs remain constantly perfectly comparable. Now, a very great number of experiments have shown to M. Regnault, that this is not always the case, and that the variations are probably due to changes, that are brought about in the molecular state of the metals, at the place of the solderings. They are felt especially in the iron and platinum pair; for the bismuth and antimony pair gives very constant results, when the temperature of the solderings is made to vary within limits, which were not exceeded in the comparative experiments, namely, from 59° to 86°. Between these limits a difference of temperature of 1°·8, produced upon the galvanometer sensibly the same deviation of 17°, whatever might be their absolute temperature; but which is very curious, and very contrary to the generally received opinion, is, that an increase of 1·8° in the difference of temperature of the two solderings of the bismuth and anti-

mony pair, produces an increase in the current the more feeble, as the difference of temperature is greater, even within the limits of 59° to 86°. It is easy to verify the result by opposing to the thermo-electric current in the differential galvanometer, so as to produce with it equilibrium, a very constant and very feeble hydro-electric current, the force of which is gradually augmented, in proportion as the temperature of one of the solderings of the bismuth and antimony pair is raised. Equilibrium being established, the difference of temperature between the two solderings is increased by 1°·8; and for this increase, a deviation is obtained, which is less in proportion as this difference was already greater.

M. Regnault had made several trials with pairs formed of wires, other than those of iron and platinum; but the iron and platinum pair is much the more regular, and the one, whose thermo-electric intensity diminishes the least with the elevation of temperature; it is not the same with an iron and copper pair; thus, the sensibility of this pair becomes completely null at 564°; then, if the temperature is raised higher, the needle, which had remained stationary from 446° to 500° retrograde, and the intensity of the current, far from increasing with the temperature, diminishes. This change of direction in the course of the current of the iron and copper pair, at a certain temperature, had already been observed, as we have mentioned, by M. Becquerel.

The researches of M. Regnault show us the difficulty there is in employing thermo-electric currents for the exact measurement of temperatures; and there is nothing astonishing in this, when once it is well established, as we have seen that these currents are not due to a simple difference in the facility with which the heat is propagated, but rather to the molecular changes, which are always more or less irregular, and which accompany this propagation.

However, if the thermo-multiplier cannot take the place of the thermometer for accuracy, in the measurement of temperatures, it may be advantageously employed in many cases, in which thermometers, even the most sensible, are neither sufficiently prompt, nor sufficiently delicate to detect sudden and inconsiderable changes of temperature, as in

Melloni's experiments upon radiant heat. MM. Becquerel and Breschet have also made a happy application of thermo-electricity for the measurement of the temperatures of the organic tissues of the body of man and of animals, by constructing mixed metallic needles of a diameter of less than a twentieth of an inch, which they introduce by the process of acupuncture into an organic tissue. It is necessary to have two needles, each composed of two very fine wires, one of copper, the other of steel, soldered together by one of their ends. The solderings of one of the mixed needles is placed in a medium, the temperature of which remains constant during the continuance of the experiment; the soldering of the other mixed needle is introduced into the tissue, whose temperature we desire to measure. The free ends of the steel of the two needles are placed in communication by a steel wire, whilst the free ends of the copper are connected by the wire of a galvanometer. When the two solderings have the same temperature, the needle of the galvanometer is not deflected; but the slightest difference of temperature, if it is only a tenth of a degree, is sufficient to produce a deviation, the direction and the extent of which serve to give exactly the value of this difference; and consequently the temperature of one of the media, when that of the other, which is constant, is known. Different observations made by placing the solderings of one of the thermo-electric needles in the mouth, and the other, for example, in the biceps muscle of a young man, have given a deviation of 4° in favour of the mouth, which corresponded, after previous experiments made on the temperature of the mouth, to 97°·88 for this latter, and only 97°·16 for that of the biceps muscle.

M. Peltier's thermo-electric pincers is also constructed upon the same principle. It consists of two very slender pairs of bismuth and antimony A and B (*fig.* 288.); these two pairs are connected one with the other by a copper wire, which unites the antimony a' of the upper pair with the bismuth b', of the lower pair; and by copper wires D and E, which, communicating with the wire of the galvanometer, complete the circuit between the upper bismuth b'', and the lower

antimony a''; F and H are the free and soldered extremities of each of the pairs which form the jaws of the pincers; which may, by means of a spring, be applied one against

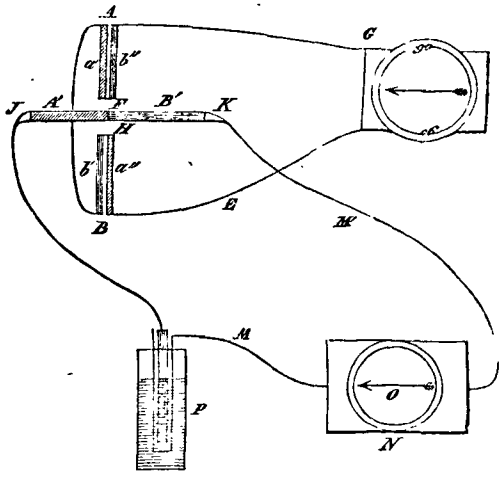


Fig. 288.

the other, or against a small portion of a wire or a metallic bar, the temperature of which at a given moment is required to be known. In *fig.* 288. the two jaws may be applied against the point of contact F, of a bar of antimony A, and a bar of bismuth B, which are traversed by the current of a pair P, the conductors of which arrive at J. and K. It was by this means that M. Peltier proved that, according to the direction of the current, which passes from the antimony to the bismuth, there is production of heat or production of cold.* Thus he obtained in the galvanometer G, of the thermo-electric pincers — 37° when the current went from the bismuth

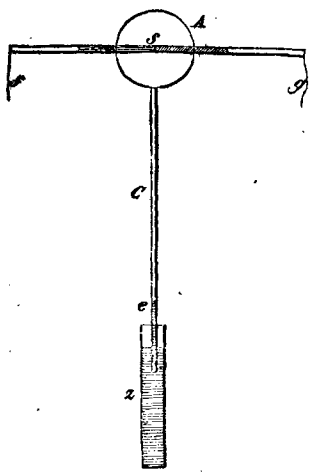


Fig. 289.

* Vol. II. p. 364.

to the antimony and +45°, namely, a deviation of 45° in the other direction, which indicated a heating instead of a cooling, when the current went from the antimony to the bismuth. In order to place this result free from all objection, M. Peltier confirmed it, as we have seen, by passing through the bulb of an air-thermometer (*fig.* 289.), a bar of antimony and bismuth, whose soldering s, was at the middle of the bulb. The current of a hydro-electric pair, arriving at the junction of the two bars by the conductors *f* and *g*, according to the direction in which it was travelling, caused the column of coloured alcohol, which was maintained in the capillary tube, and which served as an index, to rise or fall.

Comparison between the Calorific Effects of the Current, and Thermo-electric Phenomena.—Attempt at a Theory.

We have already remarked, that in the section of Chapter II. of this Volume, commencing at p. 303., the remarkable relation, that exists between the change of temperature, produced by a current, in passing from one metal into another, and the electric effects, that are brought about by a change of temperature, at the point of contact of these two same metals. Peltier, who was the first to direct attention to this subject, had thought that he was able to establish, almost as a general rule, that the greatest elevation of temperature took place, when the current passes from the inferior into the better conductor; and that the reverse is the case, when the current changes its direction. Thus, when the current passes from an iron wire into one of zinc, the temperature rises 86°, and when it passes from zinc into iron, only 55°·4; when it passes from zinc to copper, the elevation of temperature is 68°; it is not more than 57°·2, when it passes from copper to zinc. With the other metals, as we have seen, it is not merely a less elevation of temperature, but a notable depression, that is obtained, on changing the direction of the current. This takes place especially with bismuth and antimony, either when they are combined together, or when each of them is com-

bined separately with another metal. Thus, a plate of bismuth, soldered between two plates of copper, gives, with a current going from the copper to the bismuth, + 20°*, and with a current going from the bismuth to the copper, − 10°. A plate of antimony, under the same circumstances, gives − 5° with a current that goes from the copper to the antimony, and + 10° with a current that goes from the antimony to the copper. This causes the maximum of effect to take place, when the plate of bismuth and that of antimony are soldered together; for, in this case, we have, in fact, − 37°, when the current goes from the bismuth to the antimony, and + 45°, when it goes from the antimony to the bismuth.

These results can be obtained, only so long as the current is not too powerful; if its intensity is gradually increased, we arrive, first, at having neither elevation nor reduction of temperature at the soldering, which is cooled; then comes an elevation of temperature, always less than that, which is manifested, when the current changes its direction.

The remarkable effect that takes place with bismuth, shows that Peltier's law is far from being general, for it would be necessary to admit, in order to include this in it, that bismuth is a much better conductor than all the metals, which is far from being the case; moreover, antimony and bismuth, which, by their combination, give the maximum of effect, are very near to each other, in the order of their electric conductibility. These phenomena therefore, are probably due to the crystalline state of these metals; and it is very probable, that it is also to differences in their molecular structure, the other metals are indebted for the differences of temperature, that are brought about by the current at their point of junction, according as it is established in one direction or in the other. It is only over the heat, that is developed in all the length of a homogeneous wire, that the resistance of the metal to the transmission of electricity, exercises an influence, which we have recognised, and even determined. But we must take

* These degrees are those of the galvanometer-multipliers, connected with the thermo-electric pincers described above, which presses between its two jaws the point of contact of the two metals soldered together.

care to distinguish, as we have already mentioned, that Frankenheim had done * this calorific effect from the variations of temperature that take place at the points of contact of the two heterogeneous metals, that are traversed by a current. These are two phenomena of a very different order, and in no degree subject to the same laws; it is sometimes a difficult matter to unravel the part of each of these in the result observed, but they are not the less distinct.

Another proof that the latter phenomenon is essentially connected with the molecular state of the bodies, is the intimate relation that it presents with the production of thermo-electric currents, which we have seen to be an effect of the molecular modifications, produced in bodies where it takes place, by the propagation of heat. Indeed, the elevation of temperature, that is developed at the point of contact of a bar of bismuth and copper, when the current passes from the copper to the bismuth, itself produces a counter current, which goes directly from the bismuth to the copper. In like manner, the reduction of temperature, that takes place when the current passes from the bismuth to the copper, produces a counter-current, which goes from the copper to the bismuth. We may even remark, that these counter-currents should diminish, slightly, it is true, the initial current, that produces the elevation or the reduction of temperature. Thus, therefore, there is an intimate connection between the cause that produces the thermo-electric current, by an elevation or a reduction of temperature, at the point of contact of the two metals, and the cause which determines, by the passage of an exterior current, a reduction or an elevation of temperature, at the point of contact of these two same metals.

M. Frankenheim, guided by this class of considerations, made a numerous series of experiments, employing Peltier's cross apparatus, which consists of two bars of bismuth and antimony crossed one upon the other and soldered at their middle. Two of the extremities of this cross are placed in communication with the poles of a pile, and the two others

* Vol. II. p. 305.

with the ends of the wire of a galvanometer. It follows from this combination, that the heat or cold, developed by the electricity at the point of soldering, produces a thermo-electric current, which cause the needle of the galvanometer to deflect. By employing a tangent-galvanometer, and a rheostat for measuring and regulating the intensity of the voltaic current, Frankenheim recognised that the elevation of temperature, produced at the point of contact, which he terms *secondary*, is proportional to the intensity of the current, whilst the elevation of the primary temperature, that takes place in the entire conductor, by the effect of its resistance, is proportional to the square of the intensity of the current. Thus this latter temperature varies in a very decided manner, with the thickness of the metallic bars, whilst the secondary temperature is almost independent of this thickness. On this account it is that, in order to escape the influence of the former, and to study well the effect of the latter, it is better to employ thick bars to form the cross, rather than thin bars, which in addition give less constant results, because their defect of homogeneity exerts an influence proportionally more considerable.

M. Frankenheim, by employing metallic bars of different natures, has well proved that the secondary temperature does not depend, as M. Peltier had supposed, upon the conductibility of the metals, but on their thermo-electric property. He has even found, that the various metals, in their aptitude for engendering secondary heat, follow the same order as in the production of thermo-electric currents, in such sort that bismuth and antimony are at the extremities of the series, and copper in the middle. Now, as the secondary heat produces thermo-electricity, it follows that, if we have two combinations, the thermo-electric powers of which $= m : n$, we shall also have, that the variations of secondary temperature, produced by the same current, that traverses them both, shall be to each other $= m : n$. But, if the differences of temperature at the points of soldering were the same for the two combinations, we should have, that the intensities of their thermo-electric currents should be to each other $= m : n$. Now, these differences of temperature, instead of being equal, being themselves $= m : n$, it necessarily follows that the in-

tensities of the two thermo-electric currents are to each other $= m^2 : n^2$. This important law has been verified by M. Frankenheim who has also studied the reaction that the secondary current, which is produced by the heating or the cooling at the point of soldering, must exercise over the current of the pile itself. No reduction from this cause happens to that current, if the interposition of one metal in the circuit formed of another determines at its two points of contact, two equal and contrary currents; such is the case, for example, of the interposition of a bar of bismuth between two conductors of copper, where the secondary heat produces an equal heating at the two points of contact; and consequently developes two equal thermo-electric currents moving in contrary directions, which annihilate each other. But, if by the effect of the secondary action, there is a heating at one of the points of contact, and a cooling at the other, these two thermo-electric currents are added together, and the principal currents (that of the pile) suffers a diminution, which is equal to double the intensity of the current produced by the bismuth and copper pair. Perhaps it is to the action of these secondary currents, the converse of the principal current, that may be attributed the apparent differences of conductibility of metals, that seem identical. A slight difference in the molecular state and the existence, for example, of small crystals in the texture of a metal, is sufficient for the passage of electricity from one of these metals into another, arranged in a divergent direction, to give rise to a thermo-electric current. On this account it is that galvanoplastic copper, of coarser grain, diminishes less the intensity of the current than melted copper of finer grain, which presents to the current a greater number of passages from one small crystal to another. The same effect is presented with other metals; and especially with carbonised iron, in which the molecules of carbon are intimately mixed with those of iron.

It is also to a reaction, produced by the secondary current upon the principal current, that we must attribute the curious results, obtained by M. Wartmann on the diathermansy of metals; M. Wartmann thus designates the faculty possessed by two metals, of allowing the passage from one

to the other, when they are in contact, of an electric current, the intensity of which is appreciated by its calorific effect upon the helix of a Breguet's thermometer, placed in its circuit. The current itself was produced by a single pair of copper and amalgamated zinc, plunged into acidulated water. A very great number of experiments have shown that pairs, formed of two metals not soldered, present great differences in the property they possess of allowing the passage of the current, appreciated always by its calorific effect, according to the direction of this current itself; but that these differences exist especially when one of the metals at least of the pair, is of a crystalline texture, whilst they are null, when the pairs contain only ductile metals. This result indicates very clearly, that the diminution of intensity of the principal current arises from the thermo-electric current developed by the secondary heat that is produced by the passage of electricity at the point of contact of the two metals of the pair; a heat, which itself varies in intensity according as the principal current passes from the first to the second or from the second to the first.

M. Frankenheim, on plunging into a water-bath the point of soldering of a cross of iron and copper, succeeded in determining the temperature, which produces directly in this combination a thermo-electric current, equal in intensity to that, which is developed by the secondary heat liberated by a voltaic current of known power. Thus, he found that, for a current of 45°, at his tangent-galvanometer, this temperature is 68°, and that consequently the secondary heat, produced at the point of soldering, should also be 68°.

We shall not at present dwell upon the theoretical ideas of M. Frankenheim, who estimates that, in a thermo-electric chain, of which all the points of soldering have a uniform temperature, there exist, by the effect of this temperature, equal and contrary currents, that neutralise each other; that nothing more is needed than an inequality of temperature between certain points of solderings, in order to bring about the superiority of one or of several currents moving in one direction, over those moving in the other. In this point of

view, the veritable electricity of contact would be, that produced by the metals in the order of their thermo-electricity, and not in the order of their voltaic tension. We shall return to this point, when we shall have completed the study of electric sources. For the present we shall confine ourselves to proving the fact, already well established by M. Frankenheim, of the intimate connection, that exists between the secondary temperature, developed at the point of contact of two metals, by the passage of an electric current, and the thermo-electric power of these metals. Now, as it is well proved by the experiments of Svanberg, Frantz, Matteucci, and Magnus, that thermo-electricity depends upon the molecular constitution of bodies, and that it is a result of the disturbance, produced in this constitution, by the movement of heat, it follows that the secondary changes of temperature brought about in the point of contact of two heterogeneous conductors by the passage of the current, are equally dependent on this molecular constitution, and on the disturbance produced in it by the current.

If we now collate, one with the other, all the phenomena, by which heat and electricity are linked together, we everywhere see molecular influence become manifest. The production of the primary heat, that results from the passage of the current through a conductor, that presents to it a resistance, is evidently due to the molecular movements, that are brought about by this passage,—movements, whose existence becomes visible, providing there is a solution of continuity in the conductor, as in the experiment of the voltaic arc, and which is no less sensible in continuous conductors, by the alteration, that these conductors undergo, in their molecular state, when they have transmitted a current for any length of time.* We have just proved that the production of secondary heat at the points of contact, which

* Very recently, a young Swiss philosopher, M. Dufour, of Lausanne, has demonstrated that the prolonged passage of a current produced by a single pair, is able to bring about such a change in a copper wire that, even after the passage of this current has ceased, the tenacity of this wire has diminished by more than a fourth from its former tenacity. M. Adie has in like manner noticed a remarkable molecular change, which is produced at the point of contact of thermo-electric pairs, that have been for a long time in action.

generates thermo-electricity, is also eminently dependent upon molecular structure. But the difficult point for solution is to determine the laws, by which molecular movements are connected, either with electricity or with heat. For this determination, it would be necessary to operate with conducting bodies, as with those which are not so, upon perfectly regular and determinate crystals, and not upon amorphous masses, formed of metals, more or less irregularly agglomerated. We have explained the attempts, made by Svanberg and Frantz, in this direction; but they are still insufficient. Whatever may be the case, it is evident that the electric effects which are produced by the movement of heat in crystals, are exactly of the same order as those which are produced in metals by this movement; and that the difference in the mode of the manifestation of electricity is due to the difference of conductibility.

Now, if we return to the idea, which we have put forth, that atoms have an electric polarity, which they owe to a more or less rapid motion of rotation around an axis,—if, conformably to the present mechanical theories of heat, we admit that heat increases this motion of rotation, and exalts consequently, at the same time, the electric polarity, we may, in a very satisfactory manner, account for what takes place in electro-calorific phenomena. We have already said, the passage of the current, by increasing the polarity of the atoms, should exalt their velocity of rotation; and raise the temperature; in its turn, the propagation of heat increases their velocity of rotation, and should increase their electric polarity. If, in this latter case, the atoms are perfectly free to move in all directions, no exterior electric effect ought to take place; because the polar electricities of the atoms mutually neutralise each other, whether they be exalted or not by heat, since there is never more electricity of one kind, than of the other, whatever their absolute intensity may be; this is the state of things, in liquids and in very ductile metals. But, if the atoms are grouped, so as to give to the body a more or less crystalline structure, that is to say, not uniform in all directions, it ought to follow that, when the heat, in its pro-

pagation, exalts the electric polarity of certain atoms, the latter, not being susceptible of moving freely, and consequently of assuming an arrangement, which restores electric equilibrium, the integrant molecule, which they form, is found to have an electric polarity in a certain direction, and a contrary polarity in the other. All the pyro-electric phenomena of crystals, show, in fact, that the appearance of positive electricity, in one place, and negative in another, is due to the difference of molecular structure. With regard to the fact that the two electricities change places, when cooling succeeds to heating, it is due to the manner in which the atoms of the molecule become grouped, according as they receive or emit heat, namely, according as they are more or less warm, and consequently endowed with a greater or less powerful electric polarity. We shall return to this particular point, which requires to be cleared up, when we shall have completed the examination of all the causes, that give rise to the liberation of electricity.

The thermo-electric properties of metals, connected, like those of crystals, with molecular structure, are manifested under the form of a current on account of conductibility; but they arise equally from the polar state of each integrant molecule; a state, exalted by heat, and which produces an exterior effect, only so long as there is a movement of the heat, namely, a difference of temperature between the consecutive molecules. The fundamental principle in all this class of phenomena, as well for conducting bodies, as for insulators, is, that the electric state, which is acquired by the mass, is only the result of the electric state of each of the integrant molecules of this mass; whence follows, according to the manner, in which these molecules are arranged, in respect to each other, different electric manifestations.

With regard to the phenomena of secondary temperature, that is brought about by a current in passing from one metal to the other, their connection with the thermo-electric property of the two metals in contact shows that they are dependent, like this property, on the molecular constitution of the bodies, and on the disturbances, that the passage of the current brings

about in them. We have already remarked* that, if we set out from the hypothesis, that atoms are endowed with a rapid motion of rotation around an axis, a cause at once of their temperature and of their electric polarity, it may happen that this natural polarity is in accordance or discordance with the artificial polarity, that is brought about by the passage of the current. In the former case, the motion should be accelerated and the temperature should rise, whilst in the latter it falls, and the motion of rotation should diminish. But it is necessary, in order that these differences may be sensible, that the current shall not be too powerful; for, however little intensity it may have, the rotation impressed upon the atoms by artificial polarity predominates too much over that, which produces natural polarity, for their being in every case an acceleration of motion and consequently always heat, only a little more or a little less considerable, according as the polarities accord or differ.

Peltier's experiments and those of Frankenheim are altogether in accordance with this mode of explaining this class of phenomena. Thus, according to Peltier, when the current passes from iron to zinc, the temperature rises 86°; when it passes from zinc to iron, only 55°·4; when it passes from zinc to copper it rises 78°·8; and when it is from copper to zinc 14°. But the difference is much more marked, when the two metals in contact, or one at least of the two, has a very decided crystalline structure. Thus, a plate of bismuth, soldered to a plate of copper, gives, with a current of an increasing intensity, directed from the bismuth to the copper, the following results: —

Intensity of the Current.	Temperature produced at the point of Contact.
15°	27°·5
20	23 ·9
28	23 ·9
30	32 ·0
35	39 ·3

If the current is directed from the copper to the bismuth,

* Vol. I. pp. 303. and following pages.

there is obtained at the point of contact a temperature, which increases from 10° to 50°, in proportion as the intensity of the current is increased. It is evident that, as far as to a current of an intensity of 30°, the effect of the passage of the electricity is a diminution of the natural rotatory movement of the atoms, since there is a reduction of temperature; but, setting out from this intensity of 30°, the rotatory movement, impressed upon the atoms by the current is sufficiently powerful to compensate and more than compensate this diminution. A plate of antimony soldered to a plate of copper, presents a converse phenomenon; the reduction of temperature takes place, when the current passes from the copper to the antimony; and the elevation, when it passes from the antimony to the copper. This is the cause of the association of antimony and bismuth producing the maximum of effect.

But, without entering upon any hypothesis upon the cause of the atomic polarity, and of the temperature, we may yet find a great analogy between electro-thermic phenomena and those presented simply by heat. M. Clausius has shown this in a theoretic work upon the application of the mechanic theory of heat to thermo-electric phenomena, which, being connected with the loftiest notions of rational mechanics and of analysis, can find no place in a work of the nature of the present. We shall confine ourselves to pointing out, as a consequence of this work, the analogy that its author establishes between a thermic chain and a machine moved by heat. Setting out from the experimental fact that, on the one hand, in a thermo-electric pair of bismuth and antimony, the current passes at the heated point of contact from the bismuth to the antimony, and at the cooled point of contact from the antimony to the bismuth, and that, on the other hand, an exterior current, which traverses the pair, annihilates heat in the former direction, and produces it in the latter, he concludes that the point of contact maintained hot corresponds with the heated part of the caloric machine, and the point of contact maintained cold, with the condenser. Then, applying Carnot's law to these considerations, he deduces from it

the correspondence between the electric states and the variations of temperature.

It appears to us, that we may compare what takes place in this case with what transpires with an elastic fluid. If it is heated, it produces a mechanical work by its increase of elasticity; but, if it produces this mechanical work by its simple dilatation, it cools by absorbing a quantity of heat equivalent to this work. In like manner, if we heat the point of contact of the two metals, a molecular mechanical work is produced, which determines a current; but, if this same current is produced otherwise than by heating, this production brings about a molecular work, which absorbs heat, and consequently occasions a cooling. The converse would be equally true; and interesting consequences might be drawn from this comparison of the two cases,—of that in which there is a heating, and of that in which there is a cooling, — according to the nature of the work, that accompanies the passage of the current.

Clausius remarks further, that thermo-electric effects not only take place at the points of contact of the different substances, but that an electric current produces different thermic effects in the same metal, according as it travels from the hot to the cold, or from the cold to the hot; which is the same as saying that, in the interior of a same metal whose different portions are found to be at different temperatures, the heat has the tendency of propelling the electricity in a determinate direction, as well as in two metals in contact. We may add that he considers justly, as we ourselves have done, the manifestation of the electric state in the interior of a same metal, not as a direct effect, but merely as a secondary effect, of the differences of temperature; that is to say, as the result of a change produced by the heat in the molecular state. In favour of this opinion he quotes both the experiments of Magnus, and those which demonstrate, that the thermo-electric currents, that are brought about in a bar of a same metal, are due to differences of crystallisation in its interior.

In support of this mode of viewing it, we may further

quote Mr. Thomson, who has been much occupied in the application of the mechanical theory of heat to the thermo-electric phenomena, that are presented by crystallised metals, and who arrived by comparison with what takes place in other phenomena, to the conclusion that pressure or tension must develope in a homogeneous metallic mass the thermo-electric properties of crystals. Thus, he has found that a copper wire, stretched by means of a weight, presents, in respect to the same wire not stretched, thermo-electric relations exactly similar to those, which Svanberg has established between a bar, cut in a crystal of bismuth or antimony perpendicularly to the axis, and a bar cut in the direction of this axis. If, therefore, in one part of the circuit, the copper wire is stretched by a considerable weight, the other parts of the wire remaining in their natural state, and if one of the extremities of the stretched part is heated, there is established a current from the stretched part to the part not stretched through the heated point of junction; and if the wire is stretched and unstretched alternately on the two sides of the heated part, the current is instantaneously reversed at each of these alternations of tension.

It remains, therefore, evident to us that the propagation of heat is merely a means of bringing about the molecular changes that give rise to the electric manifestations; as the propagation of electricity is, in its turn, only a means of producing disturbances in the state of the particles, which bring on a rupture in the equilibrium of temperature. We shall endeavour further on to penetrate more deeply into the nature of these changes and perturbations which, as we have already said, are only modifications, brought about in the natural rotatory movement, and in the relative position of the atoms, whence flows equally the phenomena, that are presented by bodies, as well under the electric and magnetic relations, as under the chemical relations.*

* *List of the principal works relating to the subjects treated upon in this Chapter.*

Becquerel.—Electricity of the tourmaline, &c. *Ann. de Chim. et de Phys.* t. xxxvii. pp. 5 and 355.—Thermo-electric currents. *Idem.* t. xxiii. p. 131., and t. xxxi. p. 371.; t. xxxvii. p. 328., and t. xli. p. 353.

Brewster.—Pyro-electric minerals. *Ann. de Chim. et de Phys* t. xxviii. p. 161.

Haüy.—Idem. *Ann. de Chim. et de Phys.* t. i. p. 447.

Riess and *Rose.*—Pyro-electricity of minerals. *Arch. de l'Electricité*, t. iii. p. 585.

Forbes.—Idem. *Transactions of the Royal Society of Edinburgh*, t. xiii. (1832).

Seebeck.—Thermo-electric currents. *Ann. de Chim. et de Phys.* t. xxii. p. 199.

Yelin.—Idem. *Bibl. Univ.* (1823) t. xxiii. p. 38., and t. xxiv. p. 253.

Sturgeon.—Idem. *Bibl. Univ.* (1831) t. xlvii. p. 351., and t. xlviii. p. 1.

Cumming.—Thermo-electric relation. *Bibl. Univ.* (1824) t. xxv. p. 108.

Matteucci.—Various thermo-electric experiments. *Bibl. Univ.* (new series) t. xii. p. 211. ; t. xiii. p. 199. ; t. xv. p. 187. ; t. xviii. p. 353. ; and t. xviii. p. 410. *Arch. de l'Electricité*, t. ii. p. 227., and t. iii. p. 666. *Comptes rendus de l'Académie des Sciences* (1855), t. xl. p. 541.

Vorsselmann de Heer.—Thermo-electric currents of mercury. *Arch. de l'Electricité*, t. i. p. 581.

Gaugain.—Thermo-electric currents. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxiii. p. 69.

Svanberg.—Influence of crystallisation upon thermo-electric currents. *Comptes rendus de l'Acad. des Sciences*, of August 19. 1850 ; and *Arch. des Sc. Phys.* t. xv. p. 128.

Frantz.—Idem. *Ann. der Physik*, t. lxxxiii. p. 374. ; and *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xviii. p. 297.

Mousson.—Influence of the molecular state upon thermo-electric currents. *Arch. de l'Electricité*, t. iv. p. 5.

Magnus.—Idem. *Ann. de Chim. et de Phys.* (new series) t. xxxiv. p. 105.

Fourrier and *Oersted.* Thermo-electric pile. *Ann. de Chim. et de Phys.* t. xxii. pp. 201. and 373.

Pouillet.—Theory of the thermo-electric pile and measure of temperatures. *Traité de Physique. Comptes rendus de l'Acad. des Sciences*, t. iii. p. 782., and t. iv. p. 785.

Botto.—Thermo-electric pile of great resistance. *Bibl. Univ.* (1832) t. li. p. 337.

Poggendorff.—Idem. *Bibl. Univ.* (new series, 1840) t. xxx. p. 215. *Ann. de Chim. et de Phys.* t. lxxv. p. 333.

Nobili.—Thermo-electric currents. *Bibl. Univ.* (1828) t. xxxvii. p. 119.—Application of the thermo-electric pile to the measure of temperatures. *Bibl. Univ.* (1830) t. xliv. p. 225., and t. lvii. (1834) p. 1.

Melloni.—Idem. *Ann. de Chim. et de Phys.* t. xlviii. p. 198., and t. liii. p. 5.

Regnault.—Idem. *Arch des Sc. Phys.* (*Bibl. Univ.*) t. xi. p. 265. ; and *Mémoires de l'Acad. des Sciences de Paris.*

Becquerel and *Breschet.*—Idem. *Ann. de Chim. et de Phys.* t. lix. p. 113.

Peltier.—Thermo-electric pincers, and cold produced by the electric current. *Ann. de Chim. et de Phys.* t. lvi. p. 371., and t. lxxi. p. 225.

Wartmann.—Electric dia-thermansy. *Arch. de l'Electricité*, t. i. p. 74.

Frankenheim.—Relations between electro-calorific and thermo-electric phenomena. *Ann. der Physik*, t. xci.

Clausius.—Application of the mechanical theory of heat to thermo-electric phenomena. *Ann. der Physik*, t. xc.

Thomson.—Considerations upon thermo-electric currents. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxvii. p. 51., and p. 347.

CHAP. II.

ELECTRICITY PRODUCED BY MECHANICAL ACTIONS.

Development of Electricity by the Friction of insulating solid Bodies.

We have already seen that, of all the methods of developing electricity, friction is the one, that was most anciently known. If, in many cases, it seems to be the most energetic source, this is because we must not confound the electricity *collected* with the electricity *produced*. This remark applies equally to all the sources of electricity. In fact, whilst the production of electricity is an instantaneous effect, its collection requires a comparatively enormous time, especially when static electricity is in question. Thus, for example, after having rubbed a body, it is necessary to place it in communication with the instrument intended to detect the electricity, that it has acquired; and during the interval of time, that separates the two operations, many circumstances may notably diminish the electric signs, and even cause them entirely to disappear; such is the imperfection in the insulating property of the body and of the supports, the contact of the surrounding media and of the air especially. And it is not in the friction of non-conducting bodies that the difference between the electricity collected and the electricity produced, is the greatest; we shall see, on the contrary, that if we wished, for example, to conclude from the electric signs manifested by the friction of two bodies, compared with those that are produced in many cases by chemical actions, the superiority of the former mode of action over the latter case in the development of electricity, we should run the risk of falling into grave errors. Another important remark to make, and which is equally applicable to all the other sources of electricity, but the importance of which is greater, when mechanical actions are in question, in which one only of the electricities is collected, is that one

of the electricities is never liberated, without the other being equally so, and in the same proportion. This law, laid down for the first time by Wilke, is general, and the apparent exceptions, that it presents, yield before a more attentive examination of the facts. Thus Bergmann had remarked, that two goose feathers, rubbed against each other, were both raised to a positive state; and Faraday, that two bands of flannel, rubbed against each other, cross-wise, were both made negative. In these experiments, there is evidently a disapearance by friction of a very thin superficial stratum of the two substances in contact, which carries with it, the contrary electricity to that, which remains upon the bodies. Moreover, the apparent exception, of which we have just been speaking, is never presented, except in the friction of two similar bodies.

Let us now enter upon the study of the electric phenomena, that accompany friction. With this view, it is necessary to distinguish two species of friction: the one which we may call *rolling*, in which, as in the case of the two cylinders of a flatting-machine, the same point of a surface is touched by only one point of the other, without coming into contact with a second; and the friction of *sliding*, in which, on the contrary, each point of a surface is successively in contact with several points of the other. We shall have this latter in view at all times, when we shall not state the contrary. When the two surfaces, that are rubbed against each other, are unequal, we call the larger one *rubbed*, and the smaller *rubbing*; it is consequently the one, each point of which is most rubbed. There is also *central* friction; which is that which is obtained by placing two discs of the same size in rotation in a contrary direction, around a common axis, taking care that they are in contact. When the rubbed bodies are two species of a same substance, such as resin, glass, flannel, silk, velvet, cork, &c., we remark that, save the rare exceptions, which we have pointed out above, one of the pieces acquires positive electricity and the other negative; this is easily proved, by means of the dry-pile electroscope. Bergmann has observed that, when two bands of glass are so rubbed, that all the parts of the one

pass only over one part of the other, the rubbed one is negative and the rubbing one positive; the reverse is the case if the rubbed band is hot. Two plates of glass of the same size held by handles, and rubbed one against the other, from above downwards, present an identical state; in each, the upper half is positive, and the lower half negative. Two ribbons, rubbed one against the other transversely, like the two plates, are, the rubber negative, and the rubbed positive; it is the converse of the glass; an old ribbon, rubbed against a new one, is also negative. Heat tends to give to the ribbon, to which it is applied, the negative property. It is probable that it is to the greater heating, that the rubber ribbon must be negative. A very remarkable thing is that, if a cylinder of glass is covered with a substance, and is rubbed with a similar substance, it is always, whatever be the circumstances, that accompany the rubbing, the one that covers the cylinder, that is positive.

We shall not insist upon the effects of friction, in the case in which the rubbed substances are similar, but differently coloured; for, at bottom, the substances are not exactly similar, since they contain a different colouring principle; we shall pass therefore immediately to the case of the friction, brought about between dissimilar substances. We cannot do better than relate, upon this point, the interesting experiments of Coulomb, such as M. Biot, who has extracted them from a manuscript of this clever philosopher, has consigned them to his Treatise on Experimental and Mathematical Physics. A band of paper, in its natural state, being charged with the moisture of the air, acquires by friction only a feeble degree of electricity. But if it is dried and heated, against whatever body it is then rubbed, it will give sensible signs of electricity. A band of paper, heated and rubbed against a stuff of white wool, always acquires negative electricity. This same band, rubbed against metal, always acquires negative electricity, provided the metal has not a great degree of polish. In this case, it sometimes gives very feeble signs of positive electricity. The band of paper, being dried and heated, if it is rubbed against a stuff of white silk, gives signs of negative

electricity; but when the heat is passed away, it gives more frequently very feeble signs of positive electricity. The band of paper, heated and rubbed against a stuff of black silk, *new* and of a good tint, gives signs of positive electricity. The band of paper, heated and rubbed against a black stuff, *half worn out*, acquires, when it is still hot, a negative electricity; some instants after, when rubbed anew, it gives no sign of electricity; but when rubbed again, some instants after, it gives signs of positive electricity. A ribbon of white silk, heated and rubbed against metal, always gives signs of negative electricity. On allowing it to cool, and rubbing it afresh, if the metal, against which it is rubbed, is not too polished, it will continue to give signs of negative electricity; but if the metal has a very great degree of polish, it will give very feeble signs of positive electricity. Thus, for example, our cooled ribbon being rubbed against a gilt or silvered paper, which has a very great polish, will always acquire positive electricity; but, if the ribbon is heated, it will always give signs of negative electricity. It will, in like manner, always give signs of negative electricity, whether it is heated or not, when it is rubbed against the edge of a vessel, or against a metal body, that shall not have a great degree of polish, or even against a piece of tinsel; but if it is rubbed against a part of the vessel that is very polished, it will then acquire positive electricity. A black ribbon, heated or not, but silky and of a good tint, being rubbed against a polished or an unpolished metal, always gives signs of negative electricity. When the ribbon is a little silky, and the tint is feeble it sometimes gives signs of positive electricity, in the same cases as does white ribbon. A white silk ribbon, heated or not, and rubbed against a black stuff of a good tint, always gives signs of positive electricity; but if the black stuff against which the white ribbon is rubbed, is worn, and the white ribbon is heated, it will give signs of negative electricity; and, on cooling, it will again give signs of positive electricity. A silk stuff, agitated in the air with a rapid movement, always acquires negative electricity; so that the friction of the air against silk gives to the air a positive electricity. A white

ribbon of wool produces almost the same electric phenomena as a silk ribbon and a band of paper; if it is rubbed without heating it, or after it is cooled, against a very polished metal surface, such as gilded or silvered paper, or even against the side of a vessel of very polished metal, it will give signs of positive electricity; if the woollen ribbon is heated before it is rubbed, it will in all cases gives signs of negative electricity; it will give the same signs of negative electricity, if it is rubbed, without causing it to be heated, against a metal surface, which does not possess a very great degree of polish.

A ribbon of silk, a band of paper, a ribbon of wool, rubbed against a skin, retaining its hair, such as a fox's tail, or a very dry cat's skin, always acquire negative electricity, and in a greater degree than against every other species of rubber. It is known that skins, retaining their hairs, rubbed on the hairy side upon a conducting body, always acquire positive electricity.

All the peculiarities of these bodies seem to be able to be comprehended under one general principle, which is as follows: —

When the surface of two bodies are rubbed together, that one whose integrant particles are less separated from each other, and which make less excursions around their natural positions of equilibrium, appear, for this very reason, more disposed to acquire positive electricity; this tendency increases if the surface undergoes a transitory compression. Reciprocally, that one of the two surfaces, the particles of which are found to be more separated by the roughness of the other, or by any other cause whatever, is, for this very reason, more disposed to acquire negative electricity. This tendency increases if the surface undergoes a veritable dilatation. The more powerful this opposition of circumstances is, the more energetic is the development of electricity upon the two surfaces. It weakens in proportion as their state becomes more similar. A perfect equality, could such exist, would render it null.

Thus, when a solid and dry animal or vegetable substance

is rubbed against a metal surface, that possesses roughness, it gives signs of negative electricity; this is the case in which its molecules are separated. When it is rubbed against a very polished metal, which alters its surface but little, or the effect of which is confined to compressing it by parts, without separating individually the particles, of which it is composed, it gives no signs of electricity, or it gives signs of positive electricity. Heat, dilating the pores of bodies, acts upon their surface as would a rougher rubber. It disposes it, therefore, to acquire negative electricity.

When the hairs of a cat's skin are rubbed against a polished or an unpolished metal surface, they can only yield to its shock and close one upon the other; but they are in this way compressed all in a piece, without any vibration of their particles. They are thus arranged in a manner eminently favourable for acquiring positive electricity; which, indeed, they are seen to acquire, since the metal, after the friction, is always found to have negative electricity. But, if these same hairs are employed to form the tissue of a stuff, which will require that they be crowded, compacted and pressed upon each other, then, if they are rubbed against an unpolished metal surface, they will not only be pressed and compacted as before; they will, on the contrary, be separated and torn by the asperities of this surface. Thus, they must acquire negative electricity, as, indeed, they are seen to acquire, except in the case, in which the metal surface against which they are rubbed has a certain degree of polish.

In general, when one of the rubbed bodies is a tissue of animal or vegetable fibres, pressed one against the other, as a silk ribbon, a woollen stuff, or a piece of dry paper, the best rubber must be that, the tissues of which can produce only a general and transitory compression. Thus experience teaches that, in this case, nothing is preferable to a skin retaining its hair.

But, when animal or vegetable substances, rubbed against each other, both expand in the friction, the species of electricity, that is acquired by each of them, depends upon the greater or less enlargement that its pores receive; and then the slightest modifications, in the state of one or other surface,

may bring about opposite results. For example, when a white silk stuff is rubbed against a piece of dry paper, the silk generally acquires negative electricity. It would, therefore, appear to have then more tendency for this species of electricity. But, if we begin by opening the pores of the paper, by heating it, this preparation renders it more apt in its turn to acquire negative electricity; and the silk, rubbed against it, becomes positive. This faculty, which heat had exalted, diminishes in proportion as the paper cools, and as its pores are compacted. A moment arrives, when it is merely equal to that of the silk. At this epoch, the friction of these two bodies produces no sensible sign of electricity. When this instant is passed, the band of paper continuing to become cool, and its pores to be compacted, its tendency to acquire negative electricity is still weakened, whilst that of the white silk remains the same. Then this latter, being no longer counterbalanced by the state of the band of paper, it will frequently happen that the silk will acquire a negative electricity, and will consequently give to the paper a positive electricity.

The same considerations may be applied to a stuff of white silk, rubbed against a stuff of black silk. Whether the black dye gives roughness to the surface of stuffs of silk or wool, so that, in rubbing them, their pores are found to be further separated, than those of stuffs that are not dyed, or else the reunion of the colouring particles with the silk increases, under the same degree of friction and dilatation, the tendency of acquiring negative electricity, it is a fact that a stuff of *new* black silk of a good tint, being rubbed against a ribbon of white silk, always acquires this species of electricity. But when the black stuff is worn and its colour faded, if the pores of the white ribbon are dilated by heat, it acquires in its turn for negative electricity a greater tendency than the black stuff; and, consequently, it renders it positive. This disposition, as may be expected, vanishes with the accidental cause that produced it, and the cold white ribbon acquires anew positive electricity. The black dye produces upon wool the same effect as upon silk. A dry white ribbon, rubbed against a white woollen stuff, always gives signs of

negative electricity, but against woollen stuff dyed black, it gives signs of positive electricity.

Very dry woods are all negative, when they are rubbed with wax; but when they are rubbed one against the other, it is in general the denser that are negative, and the lighter, positive; thus ebony is negative with all the other woods.

Among non-conducting substances, the one the study of which, as far as regards the electricity, that is developed in it by friction, is the most important, and has been the subject of most labour, is undoubtedly glass, which presents, in this respect, remarkable peculiarities, due to the numerous variations of the state of its surfaces and of its small degree of homogeneity.

The electric properties of glass are indeed intimately connected with the state of its surface; when this surface is new, that is to say, when the glass has been recently made, it is not powerfully electric; which causes it to be unfit for the construction of electrical machines. This absence of electric virtue is due to its conductibility; but they both disappear with time. Polished and old glass is positive with the greater portion of bodies; whilst dull or ground glass is negative, when rubbed with wool, feathers, wood, paper and the hand, bodies with which polished glass is itself negative. But dull glass is positive, like polished glass, with wax, sulphur, the metals, &c. It follows consequently that, when polished and unpolished glass are rubbed against each other, the former is positive and the latter negative. Although, in general, the variable state of the surface of glass may be recognised by differences in its conducting powers, there are however cases in the which it is not so. There exists, according to Henrici, differences in the electric power of the surface of glass, which can neither be perceived by sight, nor be demonstrated by a change in the conducting power. Such is the case with the two halves of a rod of glass, one of which has been exposed to the flame of a spirit lamp, and the other of which has remained untouched. The half, that has been heated, is found to be powerfully negative, when it is rubbed with wax or with leather, whilst the other is positive.

A very prolonged or very active friction, the immersion in alcohol, or in a solution of potash, restores its positive virtue to the glass, which had lost it; however, if it is not made to undergo any operation of this kind, it may preserve for days and weeks its negative property. Rock crystal, under the same circumstances, suffers the same alteration as glass in its electric properties.

We may even render glass susceptible of acquiring negative electricity when rubbed, by plunging it into an acid, and allowing it to dry, after having previously washed it in distilled water. The immersion in an alkali does not produce the same effect.

It is evident that the action of flame consists in bringing about an alteration in the state of the surface, since mechanical means destroy the effect of this action. It is not a result of the direct action of heat; for rods of glass that are exposed to the same temperature, care being taken to enclose them in tubes of metal, so as to prevent them being in immediate contact with the flame, do not suffer any modification in their electric properties. Neither is it an effect of the action, exerted upon the glass by the products of combustion, such especially as the vapour of water on carbonic acid; for upon allowing these products, already formed, to act at a high temperature, the same result is not obtained. It is therefore probable that it is in the act itself of their formation upon the surface of the glass, that they have an action upon this surface.

Moreover, it is not only in its electric properties that glass suffers an alteration, by the modification of the surface. Lœvell and Liebig have demonstrated that a rod of glass is able to lose, by its being heated, the property that it possesses in its natural state, of causing a saturated solution of sulphate of soda, into which it is plunged, instantaneously to crystallise. This same solution crystallises immediately it is placed in contact with a part of the glass rod, that has not been heated. The part of the rod that has become inactive, may remain several days in this state; the immersion in water, followed by its drying in air, does not

suffice to restore to it its activity; for this purpose it is necessary that it be exposed for some time to the open air.

Among the substances in which the electricity, developed by friction, has been studied with care, we may cite a great number of minerals, upon which Haüy has made numerous experiments. This learned mineralogist rubbed each specimen with a woollen stuff, in order to determine whether it become positive or negative by this friction; and he thought he found that the electric characters, proper to each of the classes into which he grouped the minerals under the relation, were connected with physical properties common to all the species, comprised in the same class. However, he recognised that many circumstances, such as the transparency and the asperity of the surface, bring about modifications in the electric character of the same mineral species. These variations are in general due to the circumstance that the weakening of transparency is due either to a mixture of an heterogeneous matter interposed accidentally in the substance, or to a derangement of structure, which causes a nebulous aspect; modifications which bring about, as well as the loss of polish of the surface, a diminution in the insulating property of the body. Thus, for example, the variety of carbonate of lime called *Iceland spa*, is transparent, very insulating and positive, whilst the transparency disappears, at the same time as the insulating property and the positive electricity in the *saccharöidal* variety (statuary marble), which is negative. Thus, even quartz and topaz, which, in the state of limpid crystals, are insulating and positive, become conductors and negative, when the surface is dull and rough; but when polish is restored little by little to these fragments, they recover by degrees the intermediate states, through which they had passed, and end by entirely regaining their primitive properties in the hands of the lapidary. The state of the surfaces has so great an influence over the nature of the electricity, liberated in the friction of badly conducting bodies, that Haüy has found a crystallised mineral substance, which he has named *disthene*, which acquires with the same rubbers positive electricity on certain faces, and negative on

others, without our being able to discover apparent differences between them.

Before drawing out the series of bodies, ranged in the order of the nature of the electricity, that they liberate, on being rubbed against each other, we must occupy ourselves with the case, in which one of the rubbed bodies, being always an imperfect conductor, the other is a good conductor, such as a metal. Cavallo, Wilson, Haüy have made a great number of researches on this particular point. Cavallo had found that almost all the metals became negative, on being rubbed with the greater part of bodies, even with sealing wax. More recently, Faraday had confirmed this result with iron, copper, brass, silver, and platinum; upon thirteen substances with which he had rubbed them, he had only found sulphur, that renders them positive. Haüy had observed, when rubbed with wax, that silver, lead, bismuth, zinc, and brass are positive, whilst platinum, palladium, gold, nickel, iron, tin, arsenic, and antimony are negative.

The difference, that is remarked between these various results, is due to the fact that, when one of the rubbed bodies is very hard, in relation to the other, as a metal in relation to wax, it frequently happens that the softer is scratched by the harder; and that this latter indicates by the electroscope, not its own electricity, but that of the thin film of the substance that it removes. I have pointed out this cause of error, in endeavouring to take it into account in order to explain the anomalies that are presented by electricity developed in metals, rubbed with imperfect conductors; and I have succeeded in demonstrating in this way, what is indeed the true nature of that electricity.

We have merely to place a piece of metal upon the plate of a gold-leaf electroscope, and to rub it delicately with the fingers, in order to bring about a considerable divergence of the gold leaves, without even having need of the assistance of the condenser, it is merely necessary that the fingers be very dry; in order that the experiment shall succeed well, care is taken to hold with a well insulating glass tube, the piece of metal, in order that it shall not slip, when being

rubbed. The rubbed metals do not all acquire the same electricity in this operation; thus, antimony is negative, and bismuth positive. If we employ, as rubbing bodies, ivory, horn, cork, and various species of wood, it is found that rhodium, platinum, palladium, gold, tellurium, cobalt, and nickel, acquire negative electricity; whilst silver, copper, brass, and tin, which are in general also negative, sometimes show themselves positive, especially tin; antimony, although the most powerfully negative of all, is, however, sometimes positive; iron and zinc are sometimes positive, sometimes negative; finally, lead and bismuth are constantly positive. But if we take the precaution of rubbing the metal upon a sharp edge in very dry air, with wood very well dried, and very clean, it always acquires negative electricity, on the other hand, when the rubbed surface is great, and the rubber is moved along its whole extent, the metal becomes in general positive, especially if it is rubbed with cork. Elevation of temperature and moisture favour the liberation of positive electricity in metals, that are easily oxidisable. It is evident that these anomalies are due to the fact, that in air, and especially in moist and hot air, the surface of the majority of metals is covered with a slight film of oxide, that the rubber removes, which causes it to be no longer between the substance of the rubber (finger, wood, cork) and the metal, but rather between the film of oxide, that covers this rubber and the metal, that the friction takes place; so that, in this case, the metal acquires positive electricity, its oxide being charged with negative. But, if we operate upon a part of the surface well cleaned, and whence it is easy to remove immediately the film of oxide, as a sharp edge, then the metal always acquires negative electricity, whatever its nature may be. With cork and caoutchouc, positive electricity is more easily obtained upon metal, than with wood; because the friction, being more gentle, the film of oxide is removed more equally, and remains better adhering to the surface of the rubbing body.

The development of electricity by the friction of non-conducting bodies and metallic substances has been turned to

account, in the employment of an amalgam, with which the cushions of electrical machines, intended to serve as rubbers to the glass, are covered. These amalgams are amalgams of tin, of zinc, and of tin and zinc together; sometimes still more complicated amalgams are employed, and even a metallic combination, as mosaic gold (deuto-sulphuret of tin). Wollaston had thought that the considerable influence, which the presence of these metallic compounds exercises over the liberation of electricity, was due to a chemical action; namely, to the oxidation, that these compounds suffer in atmospheric air. In support of this opinion, he had quoted the fact that, on substituting carbonic-acid gas for atmospheric air around the plate and rubbers of the electrical machine, no more electricity is possible. But Gay-Lussac remarked that this absence of electricity was due to the hygrometric water, of which it is a difficult matter to deprive the carbonic-acid gas, and he succeeded in obtaining electricity with very oxidisable amalgams in an atmosphere of well-dried carbonic acid.

M. Peclet has taken up these experiments, speaking of the principle, that the gas is able to act in two manners, when electricity is developed by friction, either as intervening in the production of this electricity, or as a more or less conducting body. After having proved, by delicate experiments, made by means of Coulomb's balance, by a process analogous to that which we have already described *, the equality of the conducting faculties of well-dried air and carbonic-acid gas, he arranged an electrical apparatus, consisting of glass cylinder and rubbers, coated with mosaic gold, so that it might be placed entire under a receiver, furnished with a stuffing-box, traversed by a metal rod, that could, by means of gear-work, communicate to the cylinder of glass the rotatory motion, that was imparted to it exteriorly, by means of a handle. Upon operating on the air of the receiver, previously dried for twelve hours by chloride of calcium, then upon carbonic acid, introduced into the receiver in place of the air, after having been completely dried, he found that the indications

* Vol. II. pp. 142. and the following.

of an interior electroscope, which communicated by a copper wire, passed through the receiver, with a set of metal points, placed opposite and very near to the cylinder of glass, were exactly the same for both gases, provided they were equally dry. As an objection might be raised, that there remained, in these experiments, a small quantity of air, mixed with the carbonic acid, M. Peclet operated successively upon air, upon hydrogen, and upon carbonic acid, taking care, for these two latter gases, to make no experiment until after the receiver had been emptied and filled six times successively with the same gas, so that there might be a certainty of the purity of the gas. The results were always the same. Thus, it remains satisfactorily proved that, in the production of electricity by friction, the action of the air upon the more or less oxidisable portions of the rubbers, exercises no influence.

Among the substances eminently electrical, we ought also to mention Schœnbein's gun-cotton, which, hard and filamentous, is a perfect insulator and negative with all known bodies. Collodion, which is obtained in a thin pellicle by causing a solution of gun-cotton in sulphuric ether to evaporate, and which has been extended upon a surface of glass, is also electric in the highest degree and negative, except with gun-cotton, with which it is positive. If fine unsized paper is plunged, according to the process of Pelouze, into a mixture of sulphuric acid and fuming nitric acid, and is then washed in abundance of water, it assumes a yellowish and translucid appearance, similar to parchment, and acquires powerfully electric properties; for we have merely, when several sheets of paper thus prepared are superposed, to rub the upper one with the hand, in order that they may remain adherent to each other, when the first is raised, and that in separating they may give bright sparks. This paper is positive with gun-cotton and collodion, and is negative with all other substances. Its electric power is so considerable, that powerful sparks may be drawn from it, accompanied by a liberation of ozone. M. Schœnbein, who was the first to remark the powerful electric properties of this paper, proposed to employ it in the construction of

electrical machines, which consequently would have been without glass. Moreover, it is observed that, in the fabrication of ordinary paper, there is a continuous liberation of electric sparks, when, in order to dry it, the paper, still in state of pulp, is made to slide along metal cylinders heated interiorly by steam.

M. Colladon has also remarked that, in spinning machines, the operation, to which the filaments of cotton are subjected, which are compressed, drawn out, and twisted, in order to form threads, by causing them to slide over the metal surfaces, by which they are guided, liberates much electricity. The cotton threads are charged with negative electricity, and the machines acquire positive. It follows from this that, when the air is dry, the machines on the one hand, and the filaments of cotton on the other, preserve their electricity, that the corners and culminant points of the machines attract the small filaments of cotton, that are flying in the apartment, which deranges the operation of spinning, which is also hindered by the electric state of the filaments of cotton, which, by favouring their separation, their disaggregation, thus occasions a more frequent breaking of the threads. It has been also observed at New York, in houses constructed with very dry materials, that the mere friction of the soles of the shoes against the woollen carpets, with which the floors are covered whereon a person walks, liberates sufficient electricity, for this person to be charged with it in an inconvenient manner, seeing that as soon as he brings his hand or himself near to a conducting body, a spark escapes, which is frequently very disagreeable.

Before pursuing the study of the electricity, liberated by friction, we ought to give here the series of bodies classed according to the nature of the electricity, which they acquire, upon being rubbed successively against each other; but this series is established with difficulty, because of the difficulty of taking account of all the circumstances which influence the nature of the electricity that is acquired by each body. The following, however, is a tolerably exact Table of the principal substances, arranged one after the other, in such an

order that each is positive with the one that follows, and negative with that which precedes: —

Cat-skin, diamond, flannel, ivory, rock-crystal, wool, glass, cotton, linen, white silk, the dry hand, wood, sealing-wax, glue, amber, sulphur, caoutchouc, gutta-percha, prepared paper, collodion, gun-cotton.*

The analysis that we have been giving of the electrical effects, due to friction, demonstrates clearly that these effects are really due exclusively to the molecular movements, that are brought about by this mechanical action; but it is of importance to define a little better its nature, and to investigate the circumstances, that may render it more or less efficacious. M. Peclet has done this in a remarkable work, in which he has studied successively the influence of velocity, pressure, extent of the surfaces of contact, the state of the surface of bodies, their thickness and their nature. The electrical machine, employed by M. Peclet, was a glass cylinder machine, in which the rubber is placed upon the most elevated point of the cylinders; the pressure is produced by weights arranged upon the rubber; the cylinder is rounded and polished throughout, in order to avoid inequalities of friction; the electricity is collected by a metal comb, which communicates directly, by means of a copper wire covered with waxed silk, with a pendulum electrometer, the arrangement of which enables us to follow exactly the variations of tension that ensue, when the circumstances of the friction are modified. The first experiments had for their object to determine the influence of the duration of the friction upon the intensity of the electricity developed; it follows from all those which have been made with a very great number of bodies employed as rubbers, such as bare paper, paper covered with a thin foil of copper, tin, silver, and gold, tin-foil, and various stuffs of wool, silk, cotton, waxed silk, leather, &c., that the deviation of the electrometer goes on constantly increasing, for a certain time, after which it remains sensibly constant,

* Gutta percha is especially insulating at its surface; for it conducts tolerably well in the interior of its mass.

whatever, in other respects, the velocity may be, provided this velocity does not change. The permanence of the deviation is sometimes established, after the first minute; at other times, it requires a much longer period, even as much as seven minutes. This gradual and more or less rapid increase is due to several causes, in particular to the change of form, that happens to the surface of the rubber, during the first instants of the friction.

After the influence of time, that of the velocity is of importance to know. A very great number of experiments, made with rubbers of different kinds, and in favourable atmospheric circumstances, namely, when the air is very dry, have shown that the velocity with which the friction takes place is without influence over the quantity of the electricity developed; and that the pendulum of the electrometer preserves the same deviation for velocities of rotation of the glass cylinder, increasing from 1 to 8; and this equally for great and small pressures of the rubbers. When the air is moist the deviation increases a little with the velocity from 1 to 2° only; it is equally to be remarked, that permanence is not maintained, when the velocities are very small; the deviation then diminishes with the velocity, and this the more, as the air is moister; which arises, as is easily comprehended, from the loss of the electricity being proportionately more rapid; and the equilibrium between this loss and the production is established at a lower limit. There are, besides, some substances which, when employed as rubbers, produce deviations that increase with the velocity; such, for example, are silk plush, cotton cloth, linen cloth, &c. These anomalies are evidently due to the neutralisation of the electricity of the glass cylinder by the asperities of the rubber, beyond the points of contact, a neutralisation which must be less in proportion as the velocity is greater. To satisfy oneself on this we have merely to follow the motion, that the electricity imparts to the filaments of the surface of the rubbers, and especially to observe in darkness the luminous points, by which they are terminated. This influence must be greater, in proportion as the body is a better conductor, and as the filaments

of its surface are longer and more flexible; this indeed is what we observe, when we employ comparatively stuffs of silk and of cotton, or linen cloth of the same structure. Furthermore, we may at pleasure produce or cause to disappear on certain bodies the anomalies in question, by rendering the part of the rubber, that is beyond the contact, either smooth or plushy. The imperfect conductibility of the rubber by preventing the immediate escape of the electricity, that is developed upon it by friction, may exercise an influence in the contrary direction to the preceding, and diminish, with the velocity, the electric tension, which the cylinder of glass should acquire, one part of the electricity of which is taken up in this case by that of the contrary name, which the rubber retains for too long a period. Velocity is not only without influence, if care is taken to eliminate all the causes of error, over the maximum of electric tension, which is acquired by the cylinder of rubbed glass, but it never exercises any over the absolute quantity of electricity that is produced. It is easy to prove this, by placing a metal ball, communicating with the ground at such a distance from the conductor of the machine, that a spark is manifested at every turn, the movement being uniform. If the velocity is changed, the spark passes at each turn, whatever this velocity may be. Now, the discharge of the conductor, always taking place under the same tension, it is evident that the cylinder always furnishes the same quantity of electricity at each rotation, and that consequently, in a same time, the quantity of electricity produced is in proportion to the velocity, namely, to the number of rotations. This result is not, like the preceding, absolutely true, except for rubbers, which conduct electricity well, such as metals, paper, leather; for badly conducting bodies, the discharges are only manifested for a number of turns, which must be more considerable in proportion as the velocity is greater; this is easy of comprehension, from what we have said above.

To sum up, we see that velocity is without influence over the development of electricity, and that the anomalies, which are sometimes observed, arise from the humidity of the air, the asperity of the surfaces, or the imperfect conductibility of

the bodies; and it is probable also, that for excessively great velocities, the liberation of heat which accompanies the friction would be a cause of disturbance.

A very great number of experiments have demonstrated that pressure is also without any influence over the tension of the electricity developed. It follows, from an attentive examination of the facts, that the law, which consists in the deviations of the electroscope being independent of the dead pressure exercised upon the rubber, subsists also, when we consider the pressures, experienced by the points actually in contact; that is to say, that these points always suffer an increase of pressure, corresponding to that of the load, notwithstanding the increase of their number. Some anomalies presented with certain bodies, are due to the heat, that is developed by the friction. M. Peclet satisfied himself of this in a direct manner.

Neither does the length of the rubber, that is to say, the extent of the surface rubbed, exert any influence over the deviation of the balls of the electroscope; but it is not the same with the curvature of the rubber beyond the contact which has a real influence over the quantity of electricity; a quantity, which diminishes in a very sensible manner with the radius of curvature. This fact, which is presented only when the rubber is a conducting body, evidently depends upon the phenomena, that are developed at the moment of the separation of the two surfaces. There is always, in this instant, a recomposition of a certain proportion of the contrary electricities, that the two bodies had acquired by the contact, and which become free immediately on the separation. We can even recognise it, by observing in darkness luminous traces at the extremity of the cushion. Moreover, we easily conceive the influence of curvature, such as is manifested in these experiments, by remarking that the rubber must acquire, under the action of the electricity of the cylinder, a tension increasing in proportion as the curvature diminishes, and which must necessarily increase the quantity of the two electrical principles, that recompose.

The thickness, whether of the rubber, or of the glass

rubbed, has very little influence over the results, at least beyond certain limits. It is only necessary to have regard, as far as concerns glass, to the fact that, when it is hollow as a tube, instead of being solid as a rod, the interior moisture exercises an influence, which it would be wrong to attribute to the difference of thickness.

We have seen, that two species of friction may be distinguished, that of sliding, and that of rolling. In order to compare the effects of the two modes, M. Peclet employed a hollow copper cylinder, furnished at its surface with several leathers, for the purpose of enabling it to be applied accurately upon the glass cylinder of the electrical machine, on a certain extent. By means of weights, the pressure of this rubber against the glass might be made to vary. On rendering the cylinder immovable, the friction of ordinary sliding was produced; on allowing it to be free to roll around its axis, the friction of rolling was obtained. In this latter case, the rolling cylinder tends, on account of the inequalities of its surface, to separate itself from the glass cylinder; and this the more in proportion as the velocity of rotation is greater. In order to obviate this inconvenience, the best means is to employ the hands, in order to maintain the rolling cylinder upon the glass. We thus observe that the influence of velocity and pressure, in this mode of friction, as in the other, is null. With regard to the comparison of the effects, produced by the two modes of friction, experiment demonstrates that paper, skin, and metals, or their alloys, produce the same quantity of electricity, by the friction of sliding and by that of rolling. The differences, that are observed with other bodies, are due to accessory circumstances, such as filaments which, acting differently in one case and in the other, are able to draw off the electricity. Regard must also be had to an important difference between the two modes of friction; it is that, in rolling, there is continuous adhesion or pressure; and that, in friction by sliding, there is not.

Finally, it follows, from certain observations of M. Peclet's, that heat, as well as the roughness of the surface of bodies, produces a negative tendency; and that the heat, liberated

by the friction itself, always tends to give a tension more negative or less positive to that one of the two bodies, which is the least good conductor of caloric; results entirely conformable to those, which Coulomb had previously obtained, and which we have related above.

We shall terminate this paragraph by completing, by means of the data, that have been furnished to us by the study, which we have just been making, the description and the theory of electric machines, founded upon the liberation of electricity by friction, which we have hitherto merely sketched out at the commencement of this treatise.*

We have already remarked that every species of glass is not equally suitable for forming the disc of a machine. Soft glasses and hard glasses, when recently prepared, and when friction has rendered their surface scratchy, have a conducting faculty, which notably diminishes their electric power. The most suitable glass is not that which is most transparent, but that which presents on its surface small brilliant points (of silicic acid). The metallic oxides, that are found mixed with glass, and which impart to it a blue, green, or black tint, have not generally any fatal influence, except in the case in which the oxide is that of manganese, which gives a violet colour to the glass. However, it is very rare that it is the mass itself of the glass that is conducteous; the conductibility is rather superficial, and has its source in the hydroscopic nature of the surface.

Circumstances being the same, a disc of glass has an electric virtue greater, in proportion as it is thinner; which is due to this,— that the two surfaces of the disc being electrised with the same electricity, the two electric strata, by virtue of their mutual repulsion, have more density in proportion as they are nearer, and as, consequently, the thickness of the disc is less. M. Riess mentions an excellent electrical machine, the glass disc of which is scarcely $\frac{1}{10}$ in. in thickness. It would not be prudent, on account of its fragility, to go below this limit.

The glass disc, after having been rubbed, passes between

* *Vide* Vol. I. p. 19. and following pages.

the points of two metal jaws, forming part of the insulated conductor, and which embrace the edge of the disc at the extremities of its horizontal or vertical diameter. The propriety of acting in this way, in order to draw off the electricity from the two faces of the glass, is not perfectly established; for, if we seem to gain in a direct manner a greater absorption of electricity, on the other hand, we should obtain by acting only upon one of the faces, an electricity endowed with a greater intensity upon this face by the repulsive influence of the electricity of the other. However, except in certain particular cases, it is preferable to draw off the electricity at the same time from both faces. It is of importance to be able to vary the distance between the glass disc and the portion of the conductor, that draws off the electricity, because this distance must differ both with the nature of the glass, as well as with the greater or less density, with which we desire that the electricity accumulated upon the conductor, may be endowed. For obtaining these variations of distances, we may employ the system contrived by Oertling (*fig.* 290.).

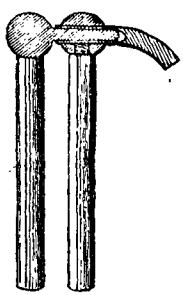


Fig. 290.

The cushions must have a perfect communication with the ground, if we desire to obtain a powerful electricity upon the disc. With regard to their width, if on the one hand it increases the extent of the rubbed surface, it has the inconvenience on the other hand, when it exceeds certain limits, of causing the disc to lose a part of the electricity, that it had acquired, by increasing its surface of contact with a conducting body. There is, therefore, a happy medium to be maintained, which depends upon the nature of the glass; the length of the cushion should not, in general, exceed two inches. Care must be taken to avoid, in the construction of rubbers, all points or sharp edges, which might possess the inconvenience of drawing off, and consequently of diminishing the electricity of the disc. It is toward the edge of the cushion, where the disc of glass abandons it, after having been rubbed, that the greatest risk arises of encountering a communication which might cause a portion of the electricity

to be lost. On this account it is that at this point are placed extensions of well insulating silk, which cover the disc, nearly as far as the conductors, in order to protect its electricity against loss, arising from the action of the air. As we have said, the leather of the cushions is covered with mosaic gold, or with an amalgam formed of tin and zinc melted together in equal proportions, with an addition of two parts of mercury. The whole, after having been agitated in a flask, is pounded in a mortar into a fine powder. Before spreading the amalgam upon the cushions, they are slightly rubbed with a few small pieces of cacao butter. A well amalgamated cushion preserves its electric activity for a long time, provided that the precaution be taken, of frequently removing the dust, which the glass plate accumulates upon it. Care must, likewise, be taken, before placing a second layer of amalgam upon the cushions, entirely to remove the old one. The glass plate, when it has been soiled by the amalgam, must also be cleaned, from time to time; and for this purpose, sulphuric ether is employed.

These are the principal precautions that must be taken, in order to obtain good electrical machines. We shall terminate

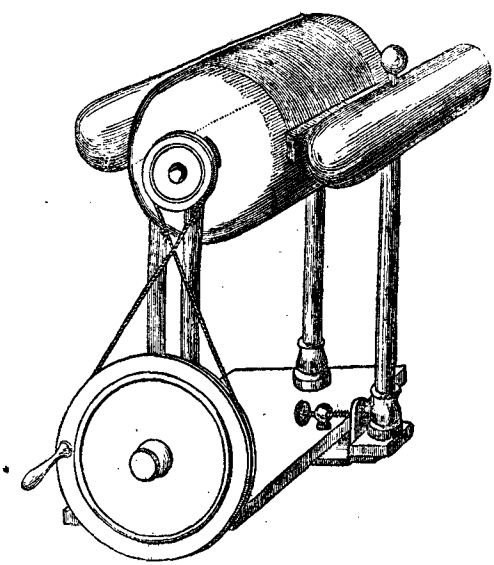


Fig. 291.

this paragraph by representing two such; one a cylinder machine (*fig.* 291.), and the other a plate machine (*fig.* 292.), constructed with all imaginable care. Although, as we have seen, the rapidity of the friction in no degree influences the

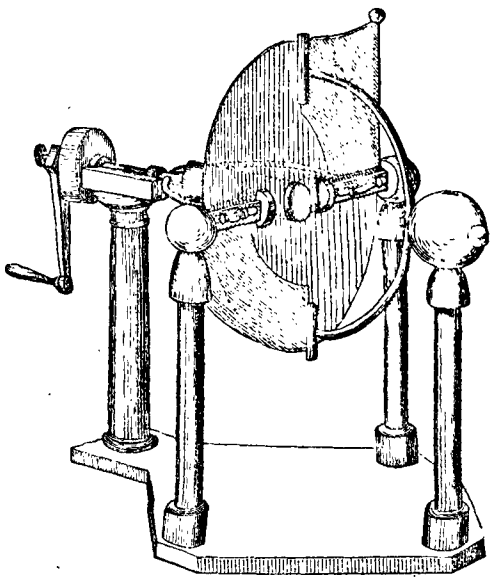


Fig. 292.

quantity of electricity produced, yet we must not turn the glass too slowly, in order not to give the electricity time to be lost between the moment, when it has been produced by the friction brought about by the cushions, and that, in which it is discharged by the conductors. The velocity of rotation is especially necessary with the cylinder machine, in which there is only one rubber, and in which, consequently, a tolerably long interval of time elapses between the moment of the development of the electricity by the friction of the glass, and that, in which it is drawn off by the insulated conductor.

Liberation of Electricity in the Friction of Bodies in Powder, of Liquids, and of Gases. Hydro-electric Machine.

When a body in powder is driven by a pair of bellows, the friction that it exercises against the end itself of the bellows,

against an inclined plate that it encounters, or against a sieve or a stuff that it traverses, is sufficient to develope electricity. Bennet made the curious remark, that chalk in powder, blown by a bellows against the plate of the electroscope, gives positive electricity if the plate is about 5 in. from the bellows, and negative, if it is about 6 in. This is due to the chalk suffering two frictions; one against the tube of the bellows, which renders it positive, and the other against the plate of the electroscope, which renders this latter negative. According to the distance, it is one or other of the two electricities, that has the superiority. Ice in powder, and snow well dried, blown by a bellows, give strong signs of electricity. When metal filings are made to slide along a smooth plate of metal, electric signs are obtained, on account of the feeble conductibility of the filings. M. Becquerel, who made a very particular study of this mode of the liberation of electricity, has observed that, when the filings of a metal are projected upon a plate of the same metal, the latter acquires positive electricity, and the filings negative; the effect is the more marked, as the filings are finer, and the blow more rapid. If the plate and the filings are not of the same metal, the effect of the division of the metal is complicated by that, which is due to the developement of voltaic electricity that takes place at the contact of the two heterogeneous metals. Thus copper filings are negative with plates of zinc, lead, tin, iron, bismuth, and antimony; zinc filings, on the other hand, are positive with plates of platinum, gold, silver, copper, and tin; they are negative with plates of zinc, bismuth, antimony, and iron; metallic oxides, as well as their sulphurets, reduced into powder, are negative, in respect to their metals. We must avoid the powders being too fine; for they attach themselves to the surface and prevent the friction of the portions, that come afterwards.

These effects are evidently connected with the force of aggregation, and, consequently, with the molecular constitution of bodies; hence, they present many anomalies, connected precisely with those which are presented by this constitution itself. Thus we see that antimony, which owes probably to its mode of crystallisation the special character, that it plays in

phenomena of this class, is negative, when in a plate, in respect to its filings, whilst it is the reverse for other metals. Heat, in general, increases the intensity of the effects, acting as does generally the division of parts. In certain cases, such, for example, as that in which the filings are of zinc, and in which the plates are but little oxidisable, namely, platinum gold, silver, or copper, the elevation of temperature produces an inversion in the nature of the electric signs, zinc being negative instead of positive.

Independently of the experiments that we have been relating, there are also a very great number of others, both more ancient, as well as more recent, upon the electric effects, produced by bodies in powder. Thus the electricity has been studied, that is, acquired by different species of powder transmitted through sieves, made with tissues of various organic substances. It has been remarked that, in general, the solid acids, as well as earths reduced into powder, acquire negative electricity, when thus sifted. The electricity developed by the friction of powders one against the other has also been studied. Thus it has been proved that sealing-wax in powder, rubbed with powdered sulphur, is positive, and that the powdered sulphur is negative; whilst the two powders equally are negative, when they are rubbed each separately with linen cloth. It is by means of the Lichtenberg figures that the nature of the electricity of each powder is easily proved. We shall relate further on some of Faraday's experiments upon the electricity developed by the friction of bodies in powder, by means of an apparatus similar to that which he employed in the study of electricity liberated by the friction of liquids and of elastic fluids. We must first occupy ourselves with this latter point.

For a long time the experiments that had been made in order to obtain electric signs by the friction of liquids had been fruitless, except in the case in which the liquid was mercury. Volta had in vain employed oil; and he had considered the liquid state as unfavourable to the manifestation of these phenomena. However, on making use of liquids, reduced to the state of very divided globules, both

insulated as well as mixed with a current of air, very decided electrical effects are obtained by their friction against solid bodies; thus ether, alcohol and liquid resins, projected against ground glass, render it very positive. A liberation of light has also been noticed in the sudden escape of very compressed air from the vessel, in which it is contained; many experiments, made by discharging air-guns, have given a similar result. But the direct proof has never been obtained that the light had an electric origin. However, Wilson had succeeded in electrising tourmaline, glass, and amber, by directing against these substances a current of air coming from a blacksmith's bellows. Henley and Lichtemberg had electrised amber and sealing-wax, by means of the air driven from an ordinary bellows; but the latter of these two philosophers had obtained no effect with the metals. In like manner, Volta had obtained no effect, on turning metals rapidly in the air, whilst he had detected some feeble effect, on operating in the same way with insulating bodies. Marx, on his side, had not been able to electrise glass any more than the metals by their friction against the air. More recently Faraday has explained perfectly these contradictory results by showing that solid bodies, such as wood, sulphur and the metals, cannot be electrised by their friction against very dry air; but are so only at such times as the air contains water or some other liquid.

We have said that, of all liquids, the one whose friction against solids gives the most decided signs of electricity, is mercury. Dessaignes, who made a great number of experiments upon this subject, had found a great difference between different substances, in regard to their faculty of being electrised by a simple immersion in mercury. Thus amber, sulphur, sealing-wax, and glass do not become electric by this simple immersion; in order to their becoming so, it is necessary that they be a little hotter than the mercury, and that the immersion be sudden, so as to produce a shock; whilst with paper, cotton, the particles of which suffer very easily a derangement of position, a slight shaking, such as arises from slow immersion, is sufficient for a liberation of

electricity to take place. Moreover, the results obtained by Dessaignes are so complex, that we shall not dwell upon them longer, on account of the difficulty of distinguishing fairly the different causes that concur in their production.

M. Perego has taken up the study of the facts, observed by Dessaignes, justly observing that this latter philosopher was wrong in directing his attention only to the electricity acquired by the body, that was plunged into the mercury, and not at all to that which is acquired by this metal. In order to obtain this latter, he pours a little mercury into a footed glass, and by means of an iron wire puts it in communication with an electroscope; he then plunges into the mercury, by one of its extremities, the substance that he desires to test, holding it between his fingers by its other extremity. So long as the substance remains plunged in the mercury, there is no electric sign, but signs are perceived at the moment when we commence to withdraw it; they become more intense, in proportion as the part withdrawn becomes more considerable; they are at their maximum at the moment, when the body ceases to be in contact with the mercury. The electricity, that is acquired by the mercury is positive, when the substance that is immersed is of an organic nature, such as paper, linen, wool, cloth, silk, sarsnet, quills, and felt; it is especially very powerful with the last four substances. The mercury is in general negative, when the immersed substances are mineral, such as rock-crystal, sulphur, glass, &c.; however, there are exceptions. We may add, that amber and sealing-wax render mercury very powerfully positive. Temperature modifies in some bodies only, and not in all, the nature of the electricity with which the mercury is charged. The precaution must be taken in these experiments of well discharging the mercury between two successive experiments; for, without this, there would be a risk of retaining electricity, probably on account of the glass, which being covered exteriorly with a slight coat of moisture, constitutes a veritable Leyden jar, of which the mercury is the inner coating, and the moist film the outer.

In these experiments felt gives so great a quantity of electricity to the mercury, that sparks may be drawn from it. It is the same with feathers; we have merely to take six or seven between the fingers, and to plunge their feathered ends into the mercury to the bottom of the vessel, in order that the mercury may give a spark on their being withdrawn. In like manner a considerable liberation of electricity is obtained, by projecting against the side of the glass, the bottom of which still retains mercury in communication with the electroscope by means of an iron wire, a jet of mercury, arising from a mass of mercury, contained in another footed glass. The experiment succeeds better, when the precaution is taken of previously heating the glass, in order to drive off all the humidity. Furthermore, we may prove the powerful liberation of electricity, that follows from the friction of mercury against glass, by observing the light, that is manifested at the top of a barometer, whose column of mercury is made to move slightly, or in a closed glass tube, deprived of air, which contains a little mercury, and which is shaken, so as to make it traverse briskly the interior of the tube from one end to the other.

We now come to the great liberation of electricity that may be produced by the friction of water, against solid bodies, — a liberation, which serves as the basis of the hydro-electric machine. The production of electricity by this machine was discovered before the cause was known; and it was even attributed to a cause totally different from the true one. It was Mr. Armstrong who first observed it in the manufactory of Sighill, near Newcastle. A mechanic, having one day accidentally placed one of his hands in the jet of steam from a high-pressure boiler, whilst the other was occupied in adjusting a weight on the lever of the valve, was very much surprised to see a brilliant spark pass between the lever and his hand; and at the same time to feel in his arms a violent shock. He obtained the same effect upon touching any part of the boiler, or any piece of metal in communication with it, Mr. Armstrong carefully analysed all these effects; he proved in this sudden expansion of steam, the production of a power-

ful positive electricity, with which the steam was charged; he did not at first find any negative electricity in the body itself of the boiler, which was due to its not being insulated; for subsequently, on insulating it, he obtained decided signs. Many other philosophers took up and varied Armstrong's experiments; but setting out as he did, from the principle that the liberation of the electricity was due to the expansion of the steam,— an erroneous principle, as we are about to see, they added nothing very important to the researches of the first observer. M. Peltier alone took advantage of it to make some curious experiments, which we shall describe further on, upon the electricity that accompanies the vapourisation of water, saturated with different salts, thinking that he saw in this, according to certain results described by Armstrong, the course of the electricity, liberated with the boilers.

It is to Mr. Faraday, that we are indebted for having discovered and well established the nature of this cause, as the result of an experimental analysis, remarkable, as are all those which the illustrious philosopher has produced. His apparatus consisted of a simple cylindrical boiler, insulated upon three blocks of lac, and furnished with a jet $4\frac{1}{2}$ in. in length (*fig.* 293.), which carried at its extremity a large stop-

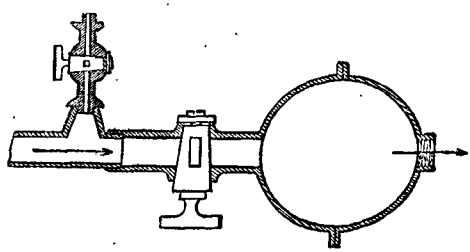


Fig. 293.

cock, and a hollow metal sphere of a capacity of 32 cubic inches. This sphere, called a *steam-globe*, was pierced with another opening, to which were adapted the apparatus, of various forms, intended to be employed for the escape of the steam. These pieces were very small, in respect to the globe, and to the tube by which it was put into communication

with the boiler; so that the globe and the tube might be considered as forming part of the boiler, and the pieces themselves might present to the escape of the steam a sufficient obstacle to occasion a considerable friction. One of the pieces (*fig.* 294.) consisted of a metal tube shaped into a funnel, and of a

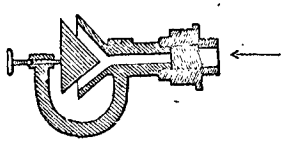


Fig. 294.

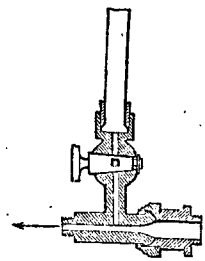


Fig. 295.

cone, which a screw caused to advance more or less into the funnel, so that the steam in escaping rubbed against the cone; moreover, this cone might be insulated, or be placed in electric communication with the funnel and the boiler. Another piece (*fig.* 295.) consisted of a tube, furnished with a stop-cock, and a feeding channel fixed above this tube, which allowed of the introduction of any other liquid into the current of steam, so that it was drawn on with it. Finally, a last piece (*fig.* 296.) contained a small cylindrical chamber C, intended to receive different liquids, so that the steam, in coming out of the steam-globe, should become mixed, on entering into this chamber, more or less with the liquid that was contained in it, and then come and rub against the cone or any other piece, that might be adapted to it. The experiments were all made with steam, whose elastic force varied between $\frac{1}{4}$ and $\frac{2}{3}$ of an atmosphere, without ever having exceeded this latter pressure. The electricity of the boiler was detected either by means of a gold-leaf electroscope, or by means of a discharging electrometer. In order to observe the electricity of the steam, it was necessary to make the latter pass through an insulated

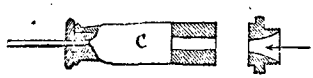


Fig. 296.

tube, furnished interiorly with diaphragms of metallic gauze, or by placing in the course of the vapour wires or plates of a conducting substance. In general it is the electricity acquired by the boiler, that Mr. Faraday always collected.

First it is easy to prove that the electricity produced is due neither to vaporisation nor to condensation. For this purpose, we have merely suddenly to remove the valve, when the steam is found under its highest tension, and no electricity at all is produced, although the vaporisation is considerable. We may in like manner demonstrate that the issue of *steam alone* is not sufficient for developing electricity; but that the presence of water in a liquid state is necessary. Thus so long as the steam-globe is empty of water, and is able to collect that, which results from the condensation of the steam, that arrives in it at the first moments of the operation, the steam in escaping produces no electricity; but as soon as the globe is sufficiently filled for the rest of the water, that condenses in it, to be drawn on by the steam, much electricity is liberated. The electricity, therefore, is entirely due to the friction of the particles of water, which the steam draws on, against the solid sides of the conduits or against the obstacles, as the cones (*fig.* 294.), which are intentionally opposed to it. Only it is necessary that it be pure; it has merely to contain in solution a proportion of a salt or of an acid, which renders it a better conductor, in order that all electrical effect shall disappear. This result is evidently due to the fact that, when the water becomes a better conductor, the two electricities liberated at the time of its friction against the solid bodies, of which one remains in this body and the other passes into the water itself, immediately recombine. In order to prove this important fact, we have merely to place in the steam-globe a small crystal of a salt, such as sulphate of soda, or a small drop of sulphuric acid, which mingles with the water that is drawn on by the steam: there is no longer any liberation of electricity; and, after having removed these substances, as soon as distilled water is replaced in the steam-globe, the liberation recommences.

In order to determine the influence of the substance against which the water is rubbed, cones (*fig.* 294.), of various kinds, which can be insulated at pleasure, must be employed. Cones of copper, boxwood, beech, ivory, sulphur, caoutchouc, varnished leather, &c., have been successively employed; they all became negative, whilst the jet of steam acquired positive electricity. A very great number of other substances, taken in the state of wires or of simple fragments, were held to the jet of steam by means of an insulator, and placed, at the same time, in connection with a gold-leaf electroscope; all were negative in different degrees,—degrees due, in great part probably to their conducting power, which would more or less facilitate the recomposition of the two electricities.

There are some substances, such as ivory, which develope very little electricity by the friction of water; also when the steam is made to pass through an ivory tube, the boiler is scarcely charged with electricity, and the current of steam is no longer sensibly electrical. This proves, still better than all the rest, that it is not vaporisation that produces the electricity. Moreover, this neutral jet serves for studying the effects of substances in wires or fragments, that are placed in it; and it is with a similar jet that we operated above.

Water, therefore, always acquires positive electricity in its friction against solid bodies. It was interesting to investigate the effect that would be produced by substances, other than water, by causing their particles to be transported by a current of steam. On making use of the apparatus (*fig.* 295.) and filling the chamber, that surmounts the stop-cock, with essence of turpentine, so as to be able to introduce it at pleasure into the passage of the steam, it is found, on allowing this essence to penetrate, that the electricity of the boiler, which was negative, when the vapour of water alone passed, becomes immediately positive, as soon as the jet of vapour is able to draw in particles of essence of turpentine; and the jet itself, from having previously been positive, becomes negative. On closing the stop-cock that gave issue to the essence, at the end of a few instants, things returned to their normal state,

because the steam soon drove away the particles of essence that had remained, and which are no longer renewed. The different species of oils and dissolved resins give the same results. Some liquids, such particularly as naphtha, give variable results, which are probably due to their being able to adhere to the rubbed body, and thus to change its nature; whilst it is necessary that they should be carried on by the current of steam.

It is very remarkable that, even in a very small quantity, oil, essence of turpentine, and dissolved resin are able to exchange the exciting power of water, which is due to the globules of water being probably covered, by the effect of the agitation of the mass, with a superficial film of these substances, in the same manner as a drop of oil, placed upon water, spreads immediately over the whole surface, forming upon it a pellicle. But this facility of the globules of water for thus covering themselves with an oily pellicle, depends upon their purity. Thus the pellicle of oil is no longer able to remain upon the surface of an alkaline water, which dissolves it, whilst the pellicle of essence of turpentine remains there.

After this study of the influence of steam, which had showed to him that it exercises no effect by itself, but merely because it is a mechanical agent, which draws along the particles, by which the friction is exerted, Faraday undertook some experiments upon compressed air, employing a powerful copper vessel of a capacity of 46 cub. in., furnished with two stop-cocks; one serving for the entry of the air, and the other for its escape. When the air had not been dried, and it was allowed to escape suddenly against the cone of copper or wood, it rendered this cone negative; an effect due evidently to the particles of water, condensed by the cold, arising from the dilatation of the air. These particles, moreover, were visible in the fog that appeared, and in the moisture, that covered the surface of the wood and the metal. But with air perfectly dry, no effect was obtained; a proof that neither *air* alone nor *steam* alone is capable of electrising bodies by friction.

On adapting the apparatus (*fig.* 296.) to the reservoir in which the air is condensed, we are able, by placing in the box C these different substances, to prove the effect which they produce on being drawn onward by the current of air; it is thus that sulphur in powder renders negative the cone of metal, that of wood, and that of sulphur; that resin in powder renders the cone of metal negative, but that of wood positive; that starch renders wood negative; that flint in very fine powder renders metal and wood powerfully positive. It is very curious that sulphur and flint in powder acquire contrary electrical states to those which these two substances assume when they are in mass; at least, when the friction takes place by means of the strong impulse, that is impressed upon them by the current of air that drags them onward. However, it would be necessary to make many experiments upon this subject, although it follows evidently from the statement that we have been making, that there is no electricity developed by friction, except so long as the rubbed bodies are both solid, or one solid and and the other liquid, and that the friction of gaseous particles against solids does not liberate any electricity.

Before terminating this paragraph, let us add, that Armstrong's discovery has given rise to the construction of a very powerful electric machine, which has been termed *hydro-electric*, and of which it remains for us to give the summary description.

This machine is composed of an insulated steam boiler *a* (*fig.* 297.), of a refrigerating box *b*, of three escape-tubes *c*, and of a conductor *d*.

The boiler is about 32 in. in length and 15 in. in diameter; it has a fireplace within it; *f* is the furnace door; *g*, the chimney; it is generally heated with charcoal; it is insulated upon the four glass pillars *v*, which are themselves carried upon a frame with wheels *u*; *s* is the safely-valve; *r*, the cock to give escape to the steam, and to put the apparatus in operation; when it is opened the steam passes first into the tube *t*, and thence is distributed into three small tubes, which traverse in a right line the refrigerating box, and

arrive at the escape-jet, by which each of these tubes is terminated.

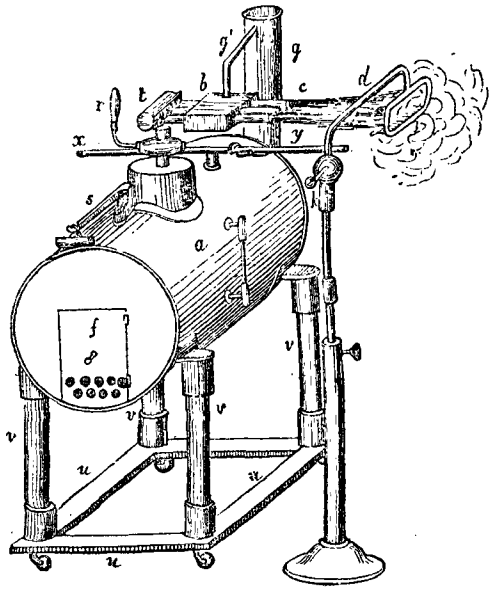


Fig. 297.

The refrigerating box *b*, contains water at the ordinary temperature; but its level is not altogether high enough for touching the steam tubes; only wicks of cotton placed upon these tubes, and plunging by their two extremities into the water of the box are moistened by capillarity, and thus cool to a certain extent both the tubes and the steam, to which they give passage. The vapours, that are produced in the box, escape into the chimney by the tube *g*.

The escape-jet is the essential piece; on the construction of this depends the electric power of the machine. After various experiments Mr. Armstong decided upon the arrangement, that is represented in (*fig.* 298.). Near its extremity, the steam-tube is enlarged into a cone; and into this cone is introduced a piece, composed of the

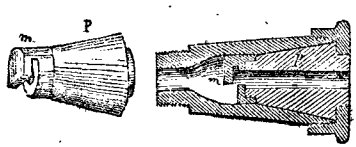


Fig. 298.

truncated cone of partridge wood *p*, the little base of which forms part with the metal piece *m*. The steam arriving directly against the metal, is broken; it is forced to gain the cleft; and there, being broken anew, in order to pass into the orifice of suitable size, which is in the axis of the truncated cone of partridge wood; the screwed ring *n* merely serves to hold the escape-jet firmly.

On traversing the box, *b*, the cooling has produced a few fine drops of water, which are carried on by the steam; and it is the friction of these drops against the partridge-wood, which developes the electricity, as has been demonstrated to us by the analysis, that Mr. Faraday has made of these phenomena. Thus the drops of water compose the rubbing body, the sides of the jet the rubbed body, and the steam is only the agent or motor, which brings about a rapid friction.

The conductor *d* has the form that is represented in the figure: it takes the electricity from the steam; it is itself insulated, and it is upon the ball *k* that the spark is seen to be drawn.

Another escape-tube *x y*, is also seen, which is intended for introducing various pulverulent substances into the path of the steam, in order to study their influence upon the nature and the quantity of the electricity produced, as Faraday has done.

That which especially distinguishes hydro-electric machines from ordinary machines is the great quantity of electricity of high tension, which they produce. A little boiler, containing only 2196 cub. in. of water, is able to give four or five sparks of 5 or 6 in. in length per second. Large boilers give results, four or five times more powerful. In certain respects, these machines seem to unite the advantages of ordinary machines of high tension, and those of voltaic apparatus, the effects of which depend principally upon the quantity of electricity developed at each instant. In opposition to these advantages, hydro-electric machines possess the inconvenience of being inapplicable to daily use, since they require, in order to give sure and energetic effects, particular

preparation and care. It is true, that atmospheric circumstances do not influence them to the same degree as they do ordinary electrical machines; on the contrary, the heat, that emanates from the furnace and from the boiler renders the glass supports very insulating; and, when charcoal deprived of moisture is used as the fuel, even prevent the escape of electricity by the current of heated air, arising from the combustion. But, on the other hand, in order to raise the steam to the requisite pressure of five or six atmospheres, the heating is obliged to be maintained for several hours; it is necessary to remove all the impurities from the interior of the apparatus, by causing it previously to heat a solution of potash, which is allowed to escape through the tubes; then by washing it with very clean rain water. Moreover, it is well to renew by a stroke of the file the internal condition of the wooden tubes, the superficial texture of which is softened and deteriorated by the hot steam. Finally, in order to obtain powerful effects, it has been found advantageous to maintain the boiler for several days in action, changing and preparing it each day afresh.

Liberation of Electricity in the Friction of two good Conducting Bodies.

The friction of two good conducting bodies is not able to give rise to the liberation of electricity in a state of tension. One of the bodies might in vain acquire by the friction positive electricity, and the other negative, since no sign of either of the two electricities would be perceptible. Indeed, the two rubbed bodies can never be separated with sufficient promptness from each other, without the immediate recomposition of the two electric principles, accumulated separately upon each of them, having previously taken place. In order to make manifest the development of electricity, that accompanies the friction of two good conducting bodies, such as two metals, it is necessary to employ the process devised by M. Becquerel. To each end of a multiplier is soldered, by a short wire, a plate of a different metal; each end is passed into a cork stopper, grooved so as to contain within it the

soldering and a part of the plate; the latter is cemented into the cork, by means of which it is held, so as not to be heated by the contact of the hand; and that, on passing simply one of the plates upon the other, no effect is produced, on account of the equality of temperature. But as soon as they are made to slide slightly with friction one upon the other, each of them acquires a contrary electricity; the recomposition of which, being able in part to be brought about by the intervention of the wire of the multiplier, gives rise to an electric current. The following is a Table of the different bodies, classed in an order such, that each of them is negative in respect to those which follow it, and positive in respect to those which precede it.* *Bismuth, palladium, platinum, lead, tin, nickel, cobalt, copper, gold, silver, iridium, zinc, iron, cadmium, arsenic, antimony, anthracite, peroxide of manganese.* We are immediately struck, on casting the eye upon this Table, that the order of the metals is exactly the same as that of their thermo-electric power; and yet it is easy to prove that the elevation of temperature, that may result from friction, is not the cause of the electricity that is liberated. Indeed, if we employ two cylinders of 4 in. in length, one of iron the other of copper, and rub them, so that the same points of the former continually traverse the whole surface of the latter, these points become more heated than the latter surface; and yet we obtain the same electric current, with regard to direction or intensity, as in the converse case, in which the surface of the former metal was rubbed with the same points of the latter. Thus, the greater or less amount of heat liberated does not exercise any influence over the phenomenon. The essential point for obtaining the greatest possible quantity of electricity is to separate the rubbed parts as promptly as possible, still maintaining the contact, so as to prevent the greater proportion of the two electricities from recombining immediately, without passing through the wire of the galvanometer.

* This manner of classing the metals indicates that the current produced by two metals, such as bismuth and antimony, rubbed together, goes from the one that is placed second in order (antimony) to the one that is first, through the wire of the galvanometer, or from the first to the second, through their point of contact.

M., Gaugain had thought he had found, in the almost entire equality, that he has observed between the intensity of the electricity, developed by friction, and that of the electricity developed under the same circumstances by an elevation of temperature equal to that, which is brought about by this friction, a proof that the electric current is due, equally in both cases, to the heating, and that the friction acts only indirectly in producing this heating. But, since it has been well proved that heat does not itself act in the production of thermo-electric currents, except by the molecular changes that it brings about, it is much more natural to see in friction a direct means of producing these changes. With regard to the equality of effect observed by M. Gaugain, it arises from the fact that electric currents, being due to the arrangement and the relative nature of the particles of the bodies in contact, their intensity must be the same, whatever be the cause, that is acting upon these bodies, provided that it acts with the same power, and that the bodies remain the same.

The following is in addition another experiment of M. Peltier's, which demonstrates that the slightest change in the position of equilibrium of the particles of a closed metallic circuit, is sufficient to produce a current, and consequently to disturb the equilibrium of the electric forces. A large circle is formed with an unannealed copper-wire, placed in connection with a galvanometer multiplier of short wire; care is taken to sustain this circle at certain distances by supports; it is then placed alternately in the magnetic meridian, in a plane perpendicular to this meridian, or in an intermediate position, so that we may be able to take account of the inductive action of terrestrial magnetism. The equilibrium of temperature being well established, one part of the wire is raised or lowered; flexions are then formed, which cannot take place without a displacement of particles, and consequently without there being an electric current. It sometimes happens that there is no effect produced; this probably takes place, when there are developed two equal currents, determined in contrary directions on each side of

the strained point. When this circumstance is presented, some portions on one side of the arc must be hardened, by means of percussion and torsion, or rather they should be again annealed. This cause of inequality is sufficient to give rise to the current, by the simple flexion of the wire. The currents cannot be attributed to terrestrial induction, since they are manifested, whatever be the position of the circuit, in respect to the magnetic meridian. With regard to the direction of the current, it is due to differences in the molecular state, of which it is impossible to take account. Moreover, we need derange this molecular state of bodies so little, in order to disturb their electric equilibrium, that we may obtain a current of variable direction by simply rubbing the wire against the fingers or with a piece of cloth; we may also excite it by drawing it through the draw-plate, after having taken the precaution of placing its two ends in communication with the wire of a galvanometer-multiplier.

More recently, Mr. Sullivan has also succeeded in obtaining a slight deviation of the needle of a multiplier, by connecting the extremities of the wire of the instrument by a wire formed of two consecutive pieces, the one of brass, the other of iron, which he caused to vibrate, after having strained it, so as to cause it to give out a musical sound. The current ceased immediately with the vibration, a proof that the heat, which might have been liberated during the vibration, in no way concurred in the phenomena, since it would not probably have disappeared instantaneously. With a bar of antimony, soldered to a bar of bismuth, so as to form in all a bar of 10 in. in length, by $\frac{2}{3}$ in. in width, and $\frac{1}{4}$ in. in thickness, the effect is decided; for putting the bar into a state of vibration, we have merely to strike it with a piece of iron,—a file for example. The amplitude of the deviations, or the intensity of the current developed, appeared to depend upon the manner, in which the vibrations are propagated along the wire. It is not necessary that the bar be composed of two metals of a different nature, in order to obtain an electric current by vibration; it is enough that its texture be not homogeneous. Thus a sensible effect is

obtained with a bar of iron, of which one portion is of hard and crystallised iron, and the other of soft and fibrous iron. These results demonstrate, in an evident manner, the direct influence of molecular movements upon the production of electricity.

Finally, the experiments of M. Ermann show well the relation, and arising from this, the independence, that exist between friction and heat in the production of electric currents. This philosopher has found, by combining different groups of metal, so as to make of them thermo-electric pairs, that a friction, exercised at their point of contact, produces the same effect as an addition of heat applied to the same point; that is to say, it brings about a current, if the temperature of the point of contact is the same as that of the ambient medium, and increases the intensity of the current already existing, if this temperature is more elevated. This effect, which Ermann calls tribo-thermic, is similar neither to that of the heat of conductibility, nor to that of radiant heat. Its production, when friction commences, and its disappearance when it ceases, are entirely independent of the duration of the action, that gives rise to it. The German philosopher seems to believe that these phenomena are due to a peculiar species of molecular vibration, excited exclusively in the points rubbed, and spreading in the conducting medium, as instantaneously as electricity does.

Liberation of Electricity in Mechanical Actions, other than Friction.

Friction is not the only mechanical action, that is a source of electricity. Every cause, that brings about a molecular movement in a solid body, produces it. Thus we have merely to cut by a cutting body, to file, or to scrape different bodies, such as gum-lac, sulphur, resin, wax, suet, chocolate, &c., in order that the fragments, in falling upon an electroscope, may charge it with electricity, and even give sparks; and the fragments detached are positive. Very slight differences in the mode of disaggregation are sufficient to cause the

nature of the electricity to vary. Thus, with a knife not sharpened, heated beech-wood gives positive fragments, and it gives negative, when cold; with a sharp knife, the fragments are negative, equally in both cases. In like manner, when we scrape sealing-wax with metal plates well-sharpened, the detached parts are negative, whilst they are positive when the cutter is dull. The number of facts in detail, described by different experimentalists, upon this subject, is so considerable, that we need merely state a few of them in order to comprehend their importance, the more so as they are not yet attached to any general law. We shall confine ourselves, therefore, to insisting on the production of electricity in a very remarkable species of disaggregation,—that which takes place in the cleavage of crystals. It is to M. Becquerel also that we are indebted, for the analysis of the mode of the liberation of electricity.

When a plate of mica is cleaved rapidly in darkness, a feeble phosphoric light is always perceived, the cause of which has been a mystery, until the experiment had been made of fixing an insulating rod to each of the opposite faces of this plate, in order to be able to separate the two faces and to present them to an electroscope. It is then found that each of the separated faces possesses an excess of the contrary electricity, the intensity of which is the greater, as the separation has been more rapid. This phenomenon always taking place, however thin the plate of mica may be, we may conclude from it, that it would be produced even to the limit, namely, if it were possible to separate the two molecules from each other. These facts prove two things:—

1st. That the molecules possess at least two faces endowed with different faculties; for, without this, we do not see why one of the plates gives one electricity and the other the contrary electricity; 2nd. That each of the faces manifests electric polarity, at the moment, when the force of aggregation is destroyed. Chemical actions, as we shall prove, lead to the same consequences.

Mica is not the only substance, that possesses the electric property of cleavage; we shall find it in the leafy talc of

St. Gothard, as well as in all crystalline substances, classed amongst bad or middling conducting bodies. We may therefore lay down as a principle that, whenever two molecules in contact are separated, each of them carries away an excess of contrary electricity, provided always that the bodies, to which they belong, are not such good conductors, that the recomposition of the two electricities, that have become free, immediately follows their separation.

In order to succeed in these experiments, we must remove from the crystals the film of hygrometric water, that generally remains adhering to their surface, and must convey the separated parts rapidly to the electroscope.

Two plates of mica, detached from the same crystal, being brought to each other and slightly pressed until they are made to adhere, come from the compression, each with the electric state, which it possessed at the instant of cleavage. The effect is particularly marked, when we slightly raise the temperature of that plate, which possessed negative electricity, in coming from cleavage.

It is easy to explain now, why we are unable to collect free electricity, when we bruise in an agate mortar crystals of substances, that conduct electricity badly, for there is an immediate recomposition of the two contrary electricities, liberated on two contiguous laminæ. It is for the same reason that no electrical effect is obtained, when we break bodies crystallised irregularly or formed of parts grouped confusedly, as tubes of glass, rods of gum-lac, &c. &c. In like manner, we perceive why no sign of free electricity is observed in the cleavage of a crystal, that is a conductor of electricity, as galena, pyrites and others, seeing that the velocity of the separation can never be sufficiently great to prevent the recomposition of the two electricities, at the moment when they are separated. In the absence of free electricity we might prove the presence of this agent, by means of the electrical effects of movement; with this view, the crystal ought to be placed in communication by two points with the ends of the wire of a galvanometer. It is infinitely probable that, on cleaving the crystal rapidly, the two electricities,

arising from the destruction of the molecular attraction, by following the wire in order to recombine, might produce a current, that would react upon the magnetised needle.

The electric effects, that are obtained in the solidification of melted bodies, are due, like the preceding, to a disaggregation; namely, to the destruction of the molecular attraction between two substances, whether homogeneous or heterogeneous. Thus, if we pour into a conical glass previously heated, some sulphur in fusion, and plunge a glass tube into it before it is cold, it is found after the solidification, when we raise the cone of sulphur, that the glass vessel possesses an excess of negative electricity and the sulphur an excess of positive. Chocolate and phosphoric acid, after their solidification in a glass, give out similar effects. M. Gay-Lussac has remarked, that the adherence of bodies together first, and then their separation by the inequality of their contraction, as takes place between glass and sulphur, are conditions indispensable, in order to obtain electricity after the fusion and the solidification of a body. Thus metals, which do not comply with these conditions, manifest no trace of it, after their solidification in glass. M. Gay-Lussac concludes, from these observations, and from some others also, that congelation, or solidification, is in no degree, as had been supposed, a source of electricity, but that it is merely a means of producing, in certain cases, a molecular disaggregation, which is itself the cause of the electricity liberated.

M. Boettiger has arrived at the same conclusion as Gay-Lussac, by bringing to the state of fusion in a platinum crucible double sulphate of copper and potash. He has not observed the least trace of electricity during the act of crystallisation; but the crucible manifested signs of positive electricity, as soon as the salt contracted with crackling, and detaching itself from the metal. It follows from all these experiments, that it requires a violent separation of the melted mass from the sides of the vessel, that contains it, in order to there being a liberation of electricity.

It is evident to the electricity that accompanies every change in the relative position of particles, that the luminous

phenomena are due, which are manifested in the crystallisation of certain bodies, and of which M. Henri Rose has made a very particular study. Arsenious acid is the first substance, upon which a phosphorescence has been observed, when it passes from the vitreous into the opaque state in crystallising. M. Rose has extended the observation to the sulphates of potash and of soda, and to other salts also. But, he has remarked, that the light, which accompanies the crystallisation, depends greatly upon the circumstances, under which this crystallisation takes place, and in particular upon the medium in which the salt is dissolved; which, in fact, influences the relative position of the particles.

The simple separation of the particles, such as takes place in compressed elastic bodies, at the moment when the pressure ceases, may also be accompanied by a development of electricity, without its being necessary that a disaggregation should take place. Thus Libes was the first to observe, that on laying upon a disc of wood covered with silk coated with a layer of elastic resin, a disc of brass fixed to a glass handle with the precaution of not allowing it to suffer any friction, if the gummed silk is slightly pressed, the metal disc acquires a very considerable excess of negative electricity; the effects are the reverse on pressing with friction; discs of silver, zinc, &c., have presented similar effects. This difference between the effects of pressure or those of friction is most remarkable, and has not admitted hitherto of explanation, except by supposing that the approximation of the particles liberates the opposite electricity to that which is liberated by their separation.

More recently, Haüy found, that a crystal of Iceland spar, and of some other mineral substances, enjoy the property of becoming electric by the simple pressure of the fingers; but this property is not so limited as he thought: for, as M. Becquerel has proved, it belongs to all bodies, even to those that are good conductors, provided they are insulated. In order to put the fact in evidence, small discs are formed of the substances, that we desire to try, of a small fraction of an inch in thickness, which are fitted to handles, that are perfectly

insulating; one handle is taken in each hand, and the discs are pressed against each other; after having withdrawn them from contact, they are presented to the tinsel disc of Coulomb's electroscope, previously electrised; it is then found that the two bodies possess a contrary electricity, provided however that the body is a bad conductor; cork and caoutchouc pressed against each other gives, the former positive, the latter negative, electricity.

Crystallised mineral substances, having a vitreous aspect, such as sulphate of lime, fluate of lime, sulphate of baryta, acquire positive electricity, when pressed with the disc of cork. Fruits, such as the orange, pressed by a disc of the same nature, communicate to it on the contrary an excess of positive electricity; in proportion as the fruit is dried and loses its electricity, the faculty of electrising is diminished. Many causes tend to modify the liberation of electricity by pressure; the first is the greater or less conductibility of the bodies. If, for example, we employ a disc of elder-pith, and a disc of metal, no effect is produced; and it is the same at all times, when the pressed substances are conductors of electricity. It appears that, at the moment when the pressure is exerted, there is formed a new state of equilibrium between the two electricities, which compose the natural electricity of the molecules in contact; so long as the pressure lasts, these two electricities are disguised one by the other; thus, notwithstanding their reciprocal attraction, and their tendency to pass from one body into the other, there is found in pressure a force, that neutralises these two actions. When the bodies are good conductors, from the moment that a diminution of pressure takes place, the two electricities recombine instantaneously, whatever be the velocity of the separation; whilst, when one of the two is not a good conductor, a diminution of pressure does not immediately bring about this recomposition, which requires more or less time for its accomplishment, according to the degree of conductibility of the two pressed bodies. The following experiment renders evident the influence of the velocity of separation in the electrical effects of pressure. Press a disc of cork upon an

orange, and then withdraw it quickly, it carries with it a very considerable excess of positive electricity; but, if it is withdrawn but slowly, this excess is found to go on diminishing; and if the velocity of separation is very slow, it becomes scarcely sensible.

Heat modifies the phenomena of pressure. If we take a very dry cork stopper, and cut it in half with a cutting instrument, pressing the two separated parts against each other, very commonly they each acquire an excess of contrary electricity; but it also frequently happens that they are not electrised. If the temperature of one of the two discs is raised a few degrees, that of the other remaining constant, it is found that the heated part takes from the other negative electricity. Two pieces of Iceland spar, at the same temperature, are not electrised by pressure; but a very slight difference of temperature suffices to give them this faculty. At equal temperatures, the two discs of cork owe their electric faculties of pressure only to a difference in the state of their surface; the one, that possesses the most asperities, always acquires negative electricity from the other. The state of surfaces in badly conducting bodies, also influence their conducting quality; for Iceland spar, which is ranged amongst the worst conducting bodies (since it preserves for several entire weeks the electricity, that has been communicated to it), becomes a sufficiently good conductor, when its polish has been removed, for its being necessary to insulate it, if we desire it to preserve its electricity. The asperities, therefore, not only determine the electricity that a badly conducting body must acquire; but they modify also its electric conductibility.

In order to measure the electric effects of pressure, we require an apparatus, that enables us to vary at pleasure the causes that influence their production. Experiments prove that the intensities increase proportionately to the pressures, for pressures that do not exceed 22 lbs. Does this law extend to higher pressures? It is a difficult matter to reply to this question. We have seen that M. Peclet had undertaken certain researches in this respect, with a view parti-

cularly of determining the influence of pressure, of velocity, &c., on the liberation of electricity in friction; but the results that he obtained, can in no way be applied to the present case. M. Becquerel thinks that it is possible, that the quantity of electricity which each body acquires, whilst it is compressed, is dependent on the degree of attraction, that the molecules of the surfaces exercise over each other; but as we are not able to appreciate the relations, existing between attraction and pressure, or the greater or less approximation of the molecules it is impossible to determine the relations between the corresponding quantities of electricity. The difficulty of separating instantaneously the two compressed bodies, without passing through successive intermediate pressure, renders the determination, so to speak, impossible, of the relations in question.

One might perhaps be led to believe that the heat, liberated in pressure, is the cause of the development of the electricity; the following experiment, due to M. Becquerel, proves the contrary, at the same time that it shows the influence of the approximation of the molecules, in order to increase the liberation of electricity, when we come to separate the bodies. Two bodies being found under the action of a certain pressure, if we wish to diminish the latter one-half, the effect of the pressure lost subsists for a time, the duration of which depends upon the degree of conductibility; so that, if we immediately withdraw these bodies from compression, each of the two carries with it an excess of contrary electricity, greater than that which is due to the pressure remaining. Now, instead of separating the bodies, when the pressure has been diminished, we restore that which had been taken away, and repeat this mode of action several times. A plate of Iceland spar and a very thin disc of cork, have given, for example, the following results. These two bodies being at first under the pressure of $8\frac{3}{4}$ lbs., the latter was reduced one-half, without deranging the contact; and one minute after they were separated; the electric tension of each disc was represented by 170: if the separation had taken place during the pressure of $8\frac{3}{4}$ lbs., the tension would have been

250; and during the pressure of $4\frac{3}{8}$ lbs. 125, the half of the preceding: it is seen therefore that, in the first case, the effect produced by the pressure, that has been lost, still subsists in part. Instead of separating the bodies, when the pressure has been reduced from $8\frac{3}{4}$ to $4\frac{3}{8}$ lbs., we restore to it the pressure that has been taken away, and repeat several times this alternate play of simple pressure and double pressure. We find, finally, that the cork disc never possesses more than the intensity 250, corresponding to the strongest pressure.

Among molecular actions, there is one that M. Bécquerel had thought to be a source of electricity; it is capillary action: but he recognised that the electricity, liberated in capillary phenomena, might be due to numerous effects, that accompany the production of these phenomena, such as the friction of the liquids against the sides of the capillary spaces; to the chemical action that takes place in certain cases, such as that, in which an electric current is obtained, by the penetration of an acid into the pores of spongy platinum, &c.

To sum up, we are able to establish as a rigorous principle demonstrated by experiment, that not only friction, but that every mechanical action which disturbs molecular equilibrium, by deranging from their natural positions the particles of a body, becomes a cause of the production of electricity; electricity, the manifestation of which is more or less sensible, according to the various conditions under which the bodies subjected to these mechanical actions are found.

General Considerations on the Liberation of Electricity by Mechanical Actions; and on its Relations with the Liberation of Heat.

We have established in the paragraphs that precede the general principle, that every disturbance impressed upon a body, from which arises a derangement in the state of its molecular equilibrium, is accompanied by a production of electricity, which is manifested more or less easily, according

to the conditions of conductibility, and of the physical constitution of the bodies disturbed. We have related the experiments of various philosophers, which show the great analogy that exists between mechanical actions and the action of heat, in the development of electricity; and which lead us to recognise, that the circumstance, which determines the nature, as well as the intensity of the electricity, is much more the body submitted to the action, than the action itself. This then is one motive more for admitting that the particles are, as we have already frequently said, endowed with an electric polarity, which in the natural state is disguised by the equilibrium, that is established between the equal and contrary polarities of all the particles of a same body. Mechanical action, like heat, comes and disturbs this equilibrium, either by changing the relative position of the particles, or else by destroying the uniformity of their natural movements of rotation; conditions, both of them necessary for equilibrium. Mechanical action does more; by disaggregating in certain cases the particles, it insulates them, and then it allows of the manifestation of their electric polarity; this is especially sensible in crystallised substances, in which the poles have a similar position on the same face of cleavage. On this account it is that, when a plate of mica is cleaved, we liberate on one of the faces the positive electricity of all the particles of this face; and on the other, consequently, the negative electricity of all its particles equally.

The production of an electric current, such as Peltier has obtained, by imparting a movement of vibration to a portion of a conductor, forming part of a closed circuit, can only be explained, by admitting that this vibrating action allows of the particles, that are subjected to it, to arrange themselves, according to their polarity,—a similar effect to that, which would be produced by the passage of an artificial current; and to give rise to a current, by the mere fact of this arrangement. This polarity, moreover, has been rendered evident, in an altogether remarkable manner, by M. Volpicelli. The manner of operating of the learned Italian consists in

bringing about in a metal rod a vibration, that is communicated to an insulating resinous stratum, with which one of the extremities of this rod is covered. It is by causing to slide, sometimes in one direction, sometimes in a contrary direction, against an insulated metal ring, the metal rod, in the part not covered by an insulating stratum, that vibrations are produced in it, in order to be propagated from it into the resinous stratum. It is observed that, when the portion, covered with this stratum, is that, which is in advance, in the progressive movements, impressed upon the rod, it is with negative electricity, that the metal part of this latter is charged; a proof that this electricity is also that which the interior surface of the insulating stratum acquires. When the movement takes plate in the other direction, positive electricity takes the place of negative. In each of the two cases, we may be sure, that the exterior surface of the insulating stratum acquires a contrary electricity to that, with which the interior surface is charged. For proving this, we have merely to cover the stratum with a small metal ring, which is thus insulated from the rod, with which it has no metallic communication. A very fine wire insulated in the air, establishes communication between this ring and an electroscope; in like manner, communication is established between the electroscope and the metal part of the rod. When we desire to collect the electricity of the exterior surface of the insulating stratum, it is preferable to make the metal rod the support, that carries the ring, against which it rubs, communicate with the ground.

We may equally cover both extremities of the rod with an insulating stratum, and cause it to slide by holding it in the hand in a portion of its length, where the metal surface is exposed. We observe that, in each excursion of the rod, the electricity of the external surface of the insulating stratum is negative at the extremity that is in advance in the movement imparted, and positive at the extremity, that is in arrear. This experiment demonstrates well, that the direction according to which the longitudinal vibration that is impressed upon the rod is propagated, influences the

polarity, that is manifested by the molecules of the insulating substance, to which this vibration is communicated.

Certain experiments, made with rods of various metals, seem to establish differences between them in regard to their faculty of developing, by the transmission of the vibrations, which they suffer, polarity under the insulating stratum. Iron and steel are in this respect very inferior to brass and silver. It is likewise disadvantageous that the metal ring, upon which the rod slides, should present roughness; it is necessary that the two surfaces, rubbed against each other, should be well polished. A dry and cold atmosphere greatly contributes to the success of the experiments. All possible precautions must be taken that no electricity shall be liberated in the contact of the hands and the insulating strata. Care must also be taken before operating, to remove the thin film of moisture, which almost always covers the insulating substance.

M. Volpicelli has also found that, on substituting at the extremities of the metal rod a stratum of sulphur for the stratum of resin, the same results are obtained. If we cover the extremities of the rod with tubes of glass, effects are also obtained, similar to those which are produced by rods all of glass; that is to say, a polarity the inverse of that, which is manifested by resin and sulphur. Finally, when a rod entirely of resin or sulphur is employed, it is remarked that if, on passing upon the ring, by which it is rubbed, it abandons a small portion of its substance, which very often happens, especially in hot weather, a polarity is always developed, but which is overthrown; it again becomes what it had been previously, if the support is changed. It is very curious, in this case, to see the polarity gradually reduced, become null, and then change its nature. This peculiar phenomenon is never presented with rods of glass, which indeed cannot be disaggregated. An important fact is, that the experiments of M. Volpicelli succeed as well and even better in vacuo than in air, — proof that the electricity of the air is not regarded.

It is very remarkable that the polarity is developed in a

much more decided manner in rods of glass than in those of resin and sulphur, which in fact do not vibrate nearly so well as the former. Let us finally add that, on covering with various substances the support, upon which the friction of the rod is brought about, we in no degree alter the direction of the polarity which depends entirely upon the direction in which the excursion of the rod takes place. This is a proof that the phenomenon is actually the result of a longitudinal vibration, impressed upon the rod and not of the friction, that it undergoes, in passing upon the support.

It would, therefore, seem to result, from the researches of M. Volpicelli, that the vibration impressed upon an insulating substance, by the intervention of a vibrating rod, would permit the molecules of this substance so to arrange themselves, as to constitute a polar chain, perpendicular to the thickness of the stratum, and presenting consequently at its two extremities contrary electricities. The direction of the vibration would influence the direction in which the poles of each of the particles would be turned. A mechanical action would therefore produce here an effect altogether analogous to a caloric action.

Thus we see heat and mechanical actions, capable of determining in bodies an identical electric state, which surprises us less, since philosophers, as we have already remarked, have been led by facts of quite another order to what has been called the mechanical theory of heat. But previously to this Becquerel had pointed out the analogy, that exists between the effects of heat and the electric effects, produced by friction. In studying them comparatively, he had succeeded in demonstrating that, when bodies are of the same nature, but bad conductors of heat, and differ from each other only in the state of their surface, the surface that is heated most acquires negative electricity, and that which is heated least, positive. This important principle will serve us further on, concurrently with others, to which we shall be led by the study of chemical action, considered as a source of electricity, to establish certain differences between the properties

and action of the positive pole, and those of the negative pole of each particle. For if, the intensities being equal, there did not exist in the exterior power of one of the poles, compared with that of the other, a certain difference, there are a great number of facts in electro-chemical phenomena, that would be inexplicable; which we shall show in endeavouring to establish directly the proofs of this difference, after having completed the study of the artificial sources of electricity.*

* *List of the principal works, relating to the subjects treated upon, in this Chapter :—*

Biot.—Friction of imperfect conductors. *Traité de Phys. experimentale et mathématique*, t. ii. p. 354.

Heintz.—Peculiar electric state of glass. *Ann. de l'Elect.* t. iii. p. 551., and *Ann. de Chim.* t. lix. p. 305.

Loevel.—Properties of glass. *Ann. de Chim. et de Phys.* t. xxix. p. 110.

Haüy.—Electricity by the friction of minerals. *Ann. de Chim. et de Phys.* t. viii. p. 383.—Electricity by pressure. *Idem.* t. v. p. 95.

De la Rive.—Electricity by the friction of metals. *Bibl. Univ.* t. lix. p. 13.

Peclet.—Influence of chemical action null in electricity by friction. *Ann. de Chim. et de Phys.* t. lxxi. p. 83.—Laws of electricity by friction. *Idem.* t. lvii. p 337.

Schoenbein.—Electric paper. *Arch. des Sc. phys.* t. ii. p. 156.

Becquerel.—Electricity by the friction of metals either in mass or in powder. *Ann. de Chim. et de Phys.* t. xxxviii. p. 113.—Electricity by the pressure and the cleavage of crystals. *Idem.* t. xxii. p. 5.; t. xxxvi. p. 265.—Electricity produced by capillary actions. *Idem.* t. xxiv. p. 337. —Comparison between the electricity and the heat liberated by friction. *Idem.* t. lxx. p. 324.

Colladon.—Mechanical effects in wire-drawing, and of the electricity liberated by friction. *Bibl. Univ.* (1836) t. i. p. 362.

Dessaigne.—Electricity by immersion in mercury. *Ann. de Ch. et de Phys.* t. ii. p. 59.

Perégo.—Idem. *Arch. de l'Elect.* t. ii. p. 395.

Armstrong.—Liberation of electricity by the expansion of steam. *Arch. de l'Elect.* t. i. p. 145.

Peltier.—Electricity of steam at high pressure. *Idem.* t. i. p. 474.

Faraday.—Electricity liberated by the friction of water, and other liquids and powders. *Idem.* t. iii. p. 369.; and *Ann. de Chim. et de Phys.* (new series) t. x. p. 88.

Gaugain.—Electricity developed by the friction of two metals. *Comptes rendus de l'Acad. des Sc. de Paris*, t. xxxvi. p. 541.; and *Arch. des Sc. phys.* t. xxii. p. 381.

Peltier.—Current produced in a conducting wire, by a molecular derangement. *Ann. de Chim. et de Phys.* t. lx. p. 261.

Sullivan.—Currents produced by the vibration of metals. *Arch. de l'Elect.* t. x. p. 480.

Ermann.—Influence of friction upon thermo-electric effects. *Arch. de l'Elect.* t. v. p. 477.

H. Rose.—Light that accompanies crystallisation. *Ann. de Pogg.*, t. lii. p. 443.

Gay-Lussac. Electricity produced by the separation of adhering bodies. *Ann. de Chim. et de Phys.* t. viii. p. 161.

Volpicelli.—Electrostatic polarity. *Comptes rendus de l'Acad. des Sc. de Paris*, t. xxxviii. (May 15. 1854); *Arch. des Sc. phys. et natur.* (*Bibl. Univ.*) t. xxviii. p 265.

Riess.—Various details on electricity by friction. *Traité de l'Electricité par Frottement*, t. ii. p. 362. and following pages.

Priestley.—Relation of old experiments on electricity by friction. *History of Electricity.*

CHAP. III.

ELECTRICITY PRODUCED BY CHEMICAL ACTIONS.

Production of Electricity by the Chemical Action of Liquids upon Solids; Voltaic Pair and Pile.

EVERY chemical action is accompanied by a disturbance in the state of equilibrium of the molecules of a body, and must, consequently, be a cause of the liberation of electricity; it is even the most powerful of all, although it does not always seem to be so. This is due to the facility, with which the two electricities tend for the most part to recompose immediately. Thus it is necessary, in this mode of production, to distinguish, as in the others, the electricity produced from the electricity collected.

Lavoisier and Laplace had long ago endeavoured, with the aid of a condenser, to obtain signs of the electricity of tension, by the action upon zinc of diluted sulphuric acid; more recently Fabroni, Wollaston, and Parrot had attributed to the chemical actions that liquids exercise upon metals, the production of the electricity in the voltaic pile; but it is only since the discovery of the galvanometer-multiplier, that we have succeeded in proving, by direct and conclusive experiments, that every chemical action gives rise to an electric current. It was in 1823 that Œrsted remarked, that if to the extremities of a galvanometer are fixed two pieces of the same metal, such as two plates of zinc, and they are plunged one after the other into a diluted acid, a deviation of the needle is observed, which indicates the production of an electric current. Becquerel found subsequently that a current is in like manner determined, by plunging into an acid or alkaline solution, the two ends of the copper wire of a galvanometer; but, in order that the current may take place, it is necessary that the liquid exercise a chemical action over the

immersed part of the wire. The same philosopher observed moreover that the direction of the current appeared to depend upon the one of the two ends of this wire, that was most sharply attacked; and that thus, it was from the one, that was last plunged in, which had the most points of contact with the liquid, that the current or positive electricity set out, in order to go into the liquid to traverse it; then to come to the other end, and to return to the first, by traversing the wire of the instrument. Yelin, at about the same period, published a series of experiments, made upon a great number of metals, from which it followed that, in plunging two pieces of the same metal into various acid and alkaline liquids, currents were observed, whose direction and intensity appeared to depend upon that of the pieces, that had been first immersed, and upon the relative nature of the liquid and the metal.

A great number of philosophers soon came, and added numerous proofs, either direct or indirect, to those which we have been indicating, in order to demonstrate, in a peremptory manner, that every chemical action gives rise to electricity, which is manifested either in the static state or that of tension, or in the dynamic state or that of current.

In order to establish some order in the study, that we are about to make of this electric source, we shall examine the liberation of electricity, to which it gives rise, by taking successively the various forms, under which chemical action may occur. This action may be that of a liquid upon a solid, that of two solutions upon each other, that of gases acting upon solids or liquids, under certain conditions; to these three forms, we shall add that, which constitutes the phenomenon of combustion, which we shall study separately, on account of the particular character, that is peculiar to it. We shall commence by the form, that we have first pointed out; namely, the action of a liquid upon a solid; this will be the subject of the present paragraph. This mode of the production of electricity is the most remarkable of all, both in itself, and because it is the cause of the electric power of the voltaic pile.

But before endeavouring to enter upon the study, it is necessary to indicate a serious difficulty, that it presents. It had long been admitted, and many philosophers still admit, that the contact of two solid and heterogeneous conducting bodies is a source of electricity; one of the bodies, by the mere fact of their contact being put into a positive state, and the other into a negative. Now, as in order to collect the electricity produced in chemical action, it is most frequently necessary to place in contact two solid conductors of different natures, they have wished to attribute to this contact, and not to chemical action, the production of electricity. However, we shall show that, in this case, it is chemical action, that is the veritable source of the electricity; and that contact is merely a condition, most frequently necessary, but not always indispensable to the manifestation of the electric signs, which it is of itself incapable of developing; for we shall see that this manifestation is able to take place by the effect of the chemical action alone without contact. Finally, we shall devote a paragraph of this Chapter to the more special study of all the facts, that have been alleged in favour of the contact theory, we shall endeavour to demonstrate, that they are easy of explanation without its being necessary to admit this theory, but that they are a consequence of the various modes of action, that produce electricity; we shall in this same Chapter, examine the various electro-chemical theories, explaining that, which appears to us best in accordance with the phenomena, in the actual state of the science. Let us now come to the object itself of this paragraph.

In order to analyse well the electric effects, that result from the chemical action of liquids upon solid bodies, we must commence by operating with the condensing electroscope. M. Becquerel, who was the first to make experiments in this manner, placed upon the plate of a condenser a metal capsule filled with a liquid; he then plunged into this liquid the extremity of a metal plate, the other end of which he held between his fingers. According to the relative nature of the two metals and of the liquid, interposed between them,

he found upon the plate of the condenser, sometimes positive, sometimes negative electricity. If the capsule was of platinum, whatever was the nature of the liquid and that of the metal, held between the fingers, the electroscope always indicated that the capsule had acquired positive electricity. With a capsule of copper, the signs were sometimes positive, sometimes negative, according as the metal, plunged into the liquid, was more or less attacked by this liquid itself. It was the same with a capsule of wood, filled with water, and in immediate contact with the upper plate of the condenser; the water, the capsule and consequently the plate acquired positive electricity when there is plunged in a plate more oxidisable than the brass of the condenser; the plate acquired negative electricity with plates less oxidisable than itself. All these results are very well explained, by setting out from the principle that, when a liquid attacks a metal, the liquid is charged with positive and the metal with negative electricity. When the experiments are made with the platinum capsule, there is chemical action only upon the plate of metal, that is plunged into the liquid, if at least the latter exercises no action upon the platinum; the liquid is thus charged with positive electricity, which spreads itself into the platinum, and thence upon the plate of the condenser, whilst the negative electricity comes out by the fingers, with which the metal is held. If the capsule, instead of being of platinum, is made of a metal attackable by the liquid, there are then two actions; that of the liquid upon the metal of the capsule, and that of the same liquid upon the metal plate, that is plunged into it. In virtue of the former action, the capsule is charged with negative electricity and the positive is dispersed into the liquid, whence it tends to come out by the metal plate, which communicates by means of the fingers with the ground; by virtue of the latter, this plate acquires negative electricity, which goes from it into the ground, whilst the positive electricity is dispersed into the liquid, and passes hence into the capsule, in order to affect the condenser. In virtue of this double action, the latter ought to receive at the same time negative and positive electricity, and according as these two electricities have

an equal or a different intensity, it gives electric signs either null, negative, or positive. The first case is realised, when the plate plunged in is of the same nature as the capsule; the second, when the metal of the capsule is more attacked than that of the plate; and the third, when it is the metal of the plate, that is more attacked than that of the capsule.

In order to avoid attributing the effects obtained, either in whole or in part, to the contact of the capsule with the plate of the condenser, it is necessary that the latter should be of the same metal as the capsule; of platinum if the latter is of platinum, of copper if it is of copper, of zinc if it is of zinc. The phenomena transpire exactly in the same manner. Moreover, in all these experiments we may employ a condenser, the plate of which is of copper, carefully gilded, or of very smooth glass, covered with a thin film of gold. We then employ a platinum capsule, in order to place in it the liquid, so that, still being insulated, we can place it in metallic communication* with one of the plates of the condenser, after having been satisfied that no electricity is developed in its contact with the plate. Then the various metallic plates, attackable by this liquid, are plunged successively into it, holding them by the fingers.

We shall quote also an experiment of Matteucci's, who demonstrates, in the most direct manner, the liberation of electricity, that accompanies the chemical action of a liquid upon a metal, in a case in which there is no possibility of causing an effect, due to the contact of two different metals, to intervene. To one of the plates of a condenser of copper is united by means of a wire, also of copper, a large plate of this metal, which is made to descend and to plunge into the water of a well, sustaining it with a silken cord; the other plate of the condenser communicates with the ground. After a few moments of contact, the condenser is found charged with negative electricity. If a small quantity of sulphuric or hydrochloric acid is poured into the water of the well, the electric signs are still more decided. When the plate, instead

* For this purpose we employ a rod of platinum, or of gilded brass, held by an insulating handle.

of being plunged into the water of the well, is placed in the liquid of a large well insulated receiver, there are no longer any signs of tension, providing that no communication is made by the hand, or any conducting body between the water of the receiver and the ground. What M. Matteucci did with copper, may be done with all the other metals, taking care that the plate plunged into the water, the wire that touches the plate of the condenser, and this plate itself, shall be of the same metal. But electric signs are obtained, only so long as the metal plate is susceptible of being attacked chemically by the liquid in which it is plunged.

A German philosopher, M. Karsten, had already made, before M. Matteucci, a great number of experiments, which demonstrate the accuracy of the principles, that we have laid down, although he has interpreted them differently, by seeing in them the proof of a development of electricity in the contact of solid and liquid bodies; but the facts observed by M. Karsten lead to a precisely contrary conclusion. He operates with wires of *zinc*, of *copper*, of *silver*, and of *platinum*, coiled into a helix at one of their extremities, which plunges into an acid, alkaline or saline solution, and communicating by the other with one of the plates of a condenser. If the wire and the plate are of zinc, the latter is charged with negative electricity. When two wires are plunged at the same time into the liquid without touching, for example, a wire of zinc and one of copper, the zinc wire, when put in contact with the plate of the condenser, is charged with negative electricity, and the copper wire with positive; and this, whatever the metal may be, of which the condenser is made. It follows, as a matter of course, that the result is the same, when a wire of silver or of platinum is substituted for the copper wire; but, if we place together in the same liquid, always without touching, a wire of copper and one of platinum, it is the copper that gives negative electricity to the condenser, and the platinum positive. All these results are perfectly in accordance with the fundamental principle, that we have established, namely, that in the chemical action of a liquid upon a metal, the metal is charged

with negative electricity and the liquid with positive, which is taken from the liquid by the less oxidisable metal, that is plunged into it. We shall return, in our last paragraph, to certain other experiments of M. Karsten's, which would seem at first sight favourable to the opinion that contact also, independently of chemical action, would be a source of electricity by itself.

The electric signs, that are obtained in the experiments, that we have just related, are in general very feeble; it requires for their manifestation a very sensitive electroscope and condenser. They have not the least relation in the world, as far as intensity is concerned, to the vivacity of the chemical action, that gives rise to them; in such sort, that one of the most energetic among these actions — that of diluted sulphuric acid upon zinc — does not give a manifestation of electricity, sensibly stronger than that which results from the simple oxidation of zinc by water. This apparent anomaly is due to a principle, that we have related at the commencement of this Chapter, — that of the immediate recomposition of the two electricities, carried by the chemical action, one into the metal, the other into the liquid. The metal and the liquid, being both very good conductors, these two electricities tend to reunite directly upon the surface, when their separation has taken place*, instead of going, one to escape to the ground and the other to act upon the condenser. There is a very feeble proportion, which escapes from this immediate neutralisation, and it is this, which is detected by the instruments. It is therefore necessary to take great care to distinguish, in the production of electricity by chemical actions, as we have done for other sources, the electricity collected, from that produced. Thus, for example, it is to the circumstance that the immediate recomposition is much less easy, that we must attribute this fact, — that the chemical action, which results upon zinc from the simple moisture

* We shall see further on, that it is not at the same points of this surface, where the liberation of electricity is made, that the recomposition is brought about; so that the latter especially takes place, when this surface is not homogeneous.

of the hand, with which it is made to communicate with the ground, often gives more decided electrical signs than those which result from the action of acidulated water upon this same metal. And yet the total quantity of electricity produced is much less in the former case, than in the latter.

But the most simple manner of diminishing the proportion of the two electricities, which recompose in proportion as they are liberated, is to cause the liquid to evaporate at the moment when it has just produced the chemical action. A capsule of an oxidisable metal is heated; then a few drops of water are poured into it, either pure or slightly acidulated; the water attacks the heated metal, and is at the same time evaporated, so that the positive electricity is carried off by the steam, and is unable to reunite with the negative, which passes from the metal to the electroscope, the gold leaves of which it makes to diverge powerfully, without the intervention of a condenser being necessary. If the quantity of liquid injected into the capsule is too considerable to be entirely evaporated, there is almost no electrical effect, because the two electricities are able to recompose, the positive not being carried away by the steam.

The electric effects that are obtained by the means, that we have been pointing out, had already been observed by Volta, and by De Saussure; and they had been attributed, by these illustrious philosophers, to the evaporation itself of the liquid. But it is easy to prove that this evaporation is not the real cause of the phenomenon, by making use of a very clean platinum capsule, heated to redness, and injecting into it either water or a liquid incapable, like water, of attacking the platinum and of being itself decomposed by the action of the heat. No electrical sign is then obtained, as M. Pouillet was the first to observe. However, if the capsule is not wide-mouthed, it sometimes happens that it is charged with negative electricity, which arises, as has been observed, from the friction against the sides of the platinum of the globules of water, that are carried on by the steam. There is also a production of electricity, if the water holds a salt in solution, or if the liquid suffers an alteration, by contact with the hot

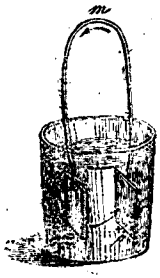
platinum. This effect, as we shall see in the following paragraph, is in some cases simply a mechanical effect, and in the greater number, an effect truly chemical, arising from the decomposition of the solution. M. Matteucci has succeeded in rendering sensible, under the same form, the electricity, due to oxidisation, without having occasion to heat the metal previously. He places at the bottom of the platinum capsule a small piece of potassium, which he bruises, in order to extend it and to make it adhere to the surface of the platinum; then, after having placed the capsule in communication with the condenser, he causes a drop of water to fall upon the potassium, the latter is decomposed with inflammation of hydrogen; as soon as the flame of the hydrogen has ceased, he raises the plate of the condenser, and it is found that the capsule has communicated to it negative electricity, whilst the hydrogen and the vapour of water formed by its combustion, have carried off the positive.

Some philosophers had attributed the electric signs, even in the case, in which the capsule is oxidisable, to the friction against the sides of the little liquid drops, drawn on by the vapour. M. Buff has arranged the experiment so as to demonstrate categorically, that the effect does indeed arise from the action of the liquid upon the metal. With this view he has enclosed the liquid in a glass retort, heated by a spirit lamp, in order thus to avoid all influence of the electricity of the flame. A wire, enveloped in a glass tube, which preserves it from contact with the vapour, plunges by one extremity into the liquid, and by the other, communicates with one of the plates of a condenser-electroscope. At the opening of the retort is placed a well insulated plate of platinum, that the vapour, on being liberated, may encounter it, and which communicates with the second plate of the condenser, or with the ground, this plate in this case also communicating with the ground. The heating of the liquid and the slow evaporation that results from it, are accompanied by a very sensible charge of the condenser; but this charge does not take place if, still leaving the plate of platinum, we withdraw the wire, that plunges into the liquid,—a proof that the simple

evaporation of a liquid does not produce electricity. Moreover, the force of the charge depends both upon the nature of the liquid as well as upon that of the wire, that is plunged into it. The plates of the condenser being of gilded copper and the liquid ordinary spring water, a negative charge is obtained, on plunging a zinc wire into the water. On substituting successively copper and silver for the zinc, we have still negative signs; but of an intensity more and more feeble.

The experiments of Buff are very analogous to those of Karsten, with this difference, that the electric signs are much more decided, on account of the evaporation of the liquid, which, in carrying away the positive electricity, diminishes the proportion of the two electricities, that recombine in an immediate manner. We shall return also to some of Buff's experiments, which, like those of Karsten, would seem, when not examined closely, favourable to the theory of contact.

It follows, from what has gone before, that it is a very difficult matter to obtain by chemical action, manifestations of static electricity of any decided intensity. It is not the same for the manifestations that take place under the dynamic or current form, chemical action being of all sources, that which produces them with the greatest energy, because we are enabled in great part to avoid the influence of immediate recomposition. Indeed, we plunge into a vessel, filled with acidulated water, a plate of an oxidisable metal, such as zinc for example; then, we unite it out of the liquid, by a wire that is soldered to it, to a plate of platinum plunged in the same liquid; then, the positive electricity, that is acquired by the liquid, from the effect of the chemical action, is able to unite to the negative that the attacked metal has retained, by traversing the platinum plate, and the wire, by which this plate is united to the metal (*fig.* 299.). A great proportion of the two electricities is neutralised in this manner, instead of taking place immediately at the surface of contact of the liquid and the attacked metal, and it thus gives rise to an electric current, which is detected by its action upon a magnetised needle, placed in



the vicinity of the conducting wire, by means of which the two metals are united; a wire, which may be that of a galvanometer.

This association of two metals, or of two solid conducting bodies, communicating metallically together and placed in a liquid, also a conductor which attacks one of them exclusively, or at least more than the other, is termed a *voltaic pair.** It is not necessary that the chemical action shall be absolutely null upon one of the metals; for the production of an electric current, it is sufficient for the action to be more powerful upon one than upon the other. We may also regard the two metals as separately giving rise to two electric currents, one of which, that arising from the metal most attacked, is more intense, and the other, that arising from the metal least attacked, is more feeble, each of the two metals serving as a conductor to the current of the other. The current collected is then the difference between the two partial unequal currents; it would be altogether null, if these two partial currents were absolutely equal; a condition almost impossible to be realised, even by employing two metals, as similar as possible with regard to their nature and the extent of their surface. *Fig.* 300. represents the case of these two partial currents, guided in contrary directions; the greater arrow indicates the direction of the definitive current, resulting from the difference of the two partial currents. We see that it is the metal most attacked, the zinc for example, that determines the direction of the definitive current; a current that comes from this metal, to direct itself through the liquid to the metal least attacked (the copper), and from this metal to the former through the conductor, by which they are connected exteriorly.

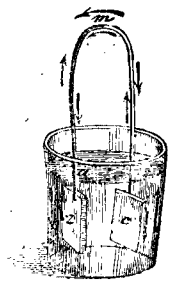


Fig. 300.

* In the pile the two metals of the same pair plunge indeed into the same liquid, but are not united metallically together; one of them is united to the metal of the following pair, and the other to the metal of the preceding pair; in Volta's theory, we call a pair the union of two metals connected metallically together, even when they plunge into two different liquid compartments

We shall continue, as is done in the contact theory, to call that metal of the pair *positive*, which, being most attacked, determines the direction of the current; and *negative* the metal least attacked, or not attacked at all, which serves only as a conductor to the definitive current. Only we must not lose sight of the fact, that positive electricity, instead of coming out by the positive metal or the one most attacked, comes out by the other, after having traversed the liquid; and that consequently it is negative, that comes out of the metal most attacked. The word positive, as far as we are concerned, will only indicate that the metal thus named, is the one which determines the direction of the current.*

Before occupying ourselves with the circumstances, which influence the intensity of the electricity liberated in a voltaic pair, and with the means of augmenting it, it is necessary to prove that the chemical action, which accompanies the production of the current, to which it gives rise, is really the cause of it.

I had already demonstrated, in 1828, by making use of a very delicate galvanometer, that a pair, formed of two plates, one of gold, the other of platinum, does not develope any current, when it is plunged in perfectly pure nitric acid, but we have merely to pour a drop of hydro-chloric acid into the nitric acid, in order to obtain a very decided current, directed from the gold to the platinum through the liquid. There is no difference between the two cases, except that, in the former, there is no chemical action, either upon one or upon the other of the two metals; whilst, in the latter, the gold is attacked, and the platinum is not, or is less attacked.

* We have found it more convenient not to change the denomination, employed from the beginning; even when it is now proved that it is from the metal called positive, that exteriorly to the pair, the negative electricity comes out; and from the metal, called negative, that positive electricity, in like manner, comes out. But this is no contradiction, seeing that, in the chemical theory, the point of departure of the two electricities is at the surface of the contact of the metal attacked and of the exciting liquid; and that we may consider the positive electricity as coming out from the metal attacked, to go into the liquid, &c. Moreover, we understand the words *positive* and *negative* in a sense independent of electricity; that is to say, in the absolute sense of the superiority of the positive body over the negative, with regard to their electro-motive powers.

In order that this experiment may succeed well, we must employ gold and platinum, prepared with great care, so that they may be free from all alloy; and care must be taken that their surface is very clean. M. Becquerel had already obtained the same result as I had, by fixing to the extremities of the galvanometer two gold wires, plunged into nitric acid; he obtained thus no effect; but, upon adding a very small quantity of hydrochloric acid, near the immersed part of one of the two wires, the magnetised needle immediately detected by its deviation the production of a current, directed through the liquid from the end attacked to the one not attacked.

To this fundamental fact, I have added several others, namely, that a pair of *platinum* and *palladium*, inactive in diluted sulphuric acid, becomes active, as soon as we pour into the solution a few drops of nitric acid, which bring about a chemical action upon the palladium; it is the same with a pair of *rhodium* and *platinum*, the action of which is null in pure nitric acid, and which gives a current in *aqua regia*, which attacks the platinum.

This is not all: after having shown, that there is no current when in a pair there is no chemical action on the part of the liquid, neither upon one or the other of the two metals of the pair, I had shown that the direction of the current changes in a same pair, when we substitute for the liquid, that attacks the first more than the second of the two metals, a liquid which attacks the second more than the first. Among the numerous examples of these inversions that I had found, I will cite that one, in which the two liquids employed are as little different as possible from each other, since the one is concentrated nitric acid, and the other diluted nitric acid. The Table that follows is composed of two columns, in which are inscribed, one below the other, the same metals, in an order such, that each metal determines the direction of the current, when it forms a pair with each of those which precede it, or is positive in respect to them. The metals of the first column are plunged into concentrated nitric acid, those of the second into diluted nitric acid. Now, the order

of the metals is not similar in the two columns, because the chemical action of the concentrated nitric acid upon the different metals is not the same as that of the diluted acid; but in each, it is always the metal that is most attacked, which determines the direction of the current.

Concentrated Nitric Acid.	Diluted Nitric Acid.
Rusty iron.	Silver.
Silver.	Copper.
Mercury.	Rusty iron.
Lead.	Iron.
Copper.	Lead.
Iron.	Mercury.
Zinc.	Tin.
Tin.	Zinc.

If the liberation of electricity was due to the contact of the two metals, the direction of the current would be independent of the nature of the liquid, interposed between them; and consequently the order of the metals would be the same in both columns. There should also have been a production of a current in the case that we have quoted above, in which, nevertheless, there was none, so long as there was no chemical action apparent.

Faraday, who has made a very numerous series of experiments upon this subject, has generalised the result, to which I had arrived, by showing that, in order to excite a current in a pair, it is necessary for the liquid to be an electrolyte, and that the more this electrolyte exercises a chemical action over one or other of the two metals of the pair, the direction of the current always depends upon that one of the two metals, that is most attacked. In order to anticipate the objection, that the absence of current might arise from the imperfect conductibility of the electrolytic liquid employed, he made use of such liquids only as conduct the current of a thermo-electric pair of bismuth and antimony; namely, of *sulphuret of potassium*, of *nitrous acid*, of *pure nitric acid*, of *concentrated sulphuric acid*, and of *a concentrated solution of potash*. These three latter liquids conduct less than the first two. He operated by placing the electrolytic liquid in two glasses, each communicating by means of a plate of platinum with the extremities of the galvanometer; he then connected the two glasses by an arc

p q, formed of the two metals of the pair, that he was desirous of testing; these two metals being united metallically at *m*, by wires of the same nature as each of them (*fig.* 301.).

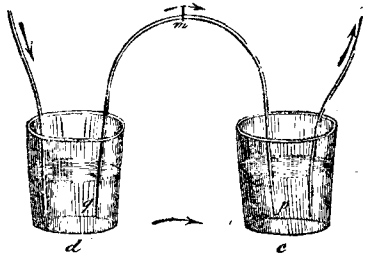


Fig. 301.

With sulphuret of potassium, the current was null, on plunging into it successively pairs of iron and platinum, of iron and gold, of iron and palladium, of nickel and gold, of nickel and palladium, of platinum and gold, of platinum and palladium; which is on account of no chemical action taking place in these various combinations. It is sufficient however to heat the point of contact *m*, of the two metals of the pair, of which the arc is formed, in order to obtain a thermo-electric current, which causes the needle of the galvanometer to deviate from 50° to 60°.

In these experiments it frequently happens that there is a production of a slight current, at the moment of the immersion of the plates of the pair in the vessels filled with the liquid; with the platinum and iron pair, the current sets out from the platinum; but Faraday satisfied himself that this effect is due to the iron being sometimes slightly oxidised; in like manner, we have merely to withdraw one of the plates from the liquid, and to expose it for a moment to the air, in order to obtain a current, which lasts for a few moments only when it is plunged in again. These different causes of disturbance are sensible, on account of the excellent conducting power of the liquid employed, and of the sensibility of the apparatus; but they disappear, if the precaution is taken of not destroying the plates of the pair, when once they are plunged into the solution, and the whole then acquires a natural and perfectly regular state. M. Ohm, who

has subjected to a very particular examination, this case of the iron and platinum pair in sulphuret of potassium, attributes the nullity of effect to the almost instantaneous formation of a thin film of sulphuret of iron upon the surface of this metal, as soon as it is immersed.

Hydrated nitrous acid, the mixture of nitric and nitrous acids, a concentrated solution of potash, are equally inactive with a great number of pairs. Silver and platinum, which gives a powerful current with the most slightly acid solution, gives none with the solution of potash; it is sufficient, however, slightly to heat their point of contact, in order to have a very decided current, due to thermo-electricity.

It is useless now to remark that, when with these same liquids, we make use of pairs, that give rise to a current, we may always prove the existence of the chemical action upon one of the metals of the pair. But when the liquid is sulphuret of potassium, there is a production of a sulphuret, that forms upon the metal attacked sometimes a non-conducting film, as upon cadmium and tin, consequently impermeable to the current; sometimes, on the other hand, a conducting film, but not soluble, which in like manner stops the current, because the chemical action ceases, as with lead and bismuth; sometimes a non-conducting but soluble film, as with zinc, which allows the current to continue to exist.

A very curious phenomenon, also observed by Faraday, is the inversion that takes place in the direction of the current of the copper and silver pair, plunged into the solution of sulphuret. The copper is at first the one, from which the current sets out, and the silver is not tarnished; then the action ceases, and it is the silver that gives rise to the current, and which is covered with the sulphuret, whilst the film, that had been formed upon the copper, is dissolved; a few moments after, the copper again becomes positive, and thus the direction of the current and the chemical action change simultaneously several times in succession. Moreover, Faraday has found a great number of examples of inversion in the direction of the current produced by the same pair, according to the liquid into which it is plunged; so that he has completely confirmed the principle, that I had

established; namely, that the voltaic series of metals is not absolute, but that it depends upon the nature of the liquid employed as an exciter. The following is a Table, that contains the results of experiments made with seven liquids and ten different metals; and which is composed of seven columns, in each of which the metals are ranged in an order, variable with the liquid employed. Each metal is marked by a number, which indicates the order in which it ought to be placed, if the liquid employed is a diluted acid, the direction of the current being always such that the metal, that follows, is the one that determines the direction of the current, when it forms a pair with one of those, that precede: —

Diluted Nitric Acid.	Diluted Sulphuric Acid.	Hydrochloric Acid.	Concentrated Nitric Acid.	Solution of caustic Potash.	Colourless Hydrosulphuret of Potash.	Yellow Hydrosulphuret of Potash.
1. Silver.	1. Silver.	3. Antimony.	5. Nickel.	1. Silver.	6. Iron.	6. Iron.
2. Copper.	2. Copper.	1. Silver.	1. Silver.	5. Nickel.	5. Nickel.	5. Nickel.
3. Antimony.	3. Antimony.	5. Nickel.	3. Antimony.	2. Copper.	4. Bismuth.	4. Bismuth.
4. Bismuth.	4. Bismuth.	4. Bismuth.	2. Copper.	6. Iron.	8. Lead.	3. Antimony.
5. Nickel.	5. Nickel.	2. Copper.	4. Bismuth.	4. Bismuth.	1. Silver.	8. Lead.
6 Iron.	6. Iron.	6. Iron.	6. Iron.	8 Lead.	3. Antimony.	1. Silver.
7. Tin.	8. Lead.	8. Lead.	7. Tin.	3. Antimony.	7. Tin.	7. Tin.
8. Lead.	7. Tin.	7. Tin.	8. Lead.	9. Cadmium.	2. Copper.	9. Cadmium.
9. Cadmium.	9. Cadmium.	9. Cadmium.	10. Zinc.	7. Tin.	10. Zinc.	2. Copper.
10. Zinc.	10. Zinc.	10. Zinc.	9. Cadmium.	10. Zinc.	9. Cadmium.	10. Zinc.

Mr. Faraday has also made a very great number of experiments in exciting a chemical action, and consequently an electric current, by means of heat applied to one of the metals of a pair; he has more particularly examined the case, in which the pair, being formed of the two similar metals, one of the two is heated, and not the other, at the moment of plunging into the liquid. It is clear that a difference arises in the chemical action of the liquid upon the two metals; but these are complex effects, because the liquid frequently suffers itself a chemical alteration by the action of the heat; and regard must be had to the thermo-electric current, which frequently takes place in this case; we shall not, therefore, for the present, dwell upon this, as we must return to the subject further on.

But an essential point, established by Mr. Faraday, upon which we must insist, is the possibility of obtaining a current capable of itself producing a chemical decomposition, with a

single metal submitted to chemical action, without the intervention consequently of a metallic contact between two heterogeneous metals. In order to obtained this result, a plate of platinum *b* is plunged into acidulated water (*fig.* 302.),

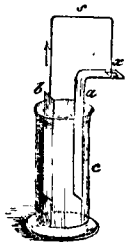


Fig. 302.

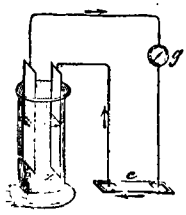


Fig. 303.

and a plate of zinc *a c*, bent horizontally in the part exterior to the liquid; a piece of litmus paper, moistened with a solution of iodide of potassium, is placed upon the zinc plate at *x*, and the end of a platinum wire *s*, soldered to the plate of the same metal, is also placed in contact with this paper. The iodide is immediately decomposed, which shows that the current, that produces this decomposition, results only from the chemical actions upon the zinc; for there is no metallic contact between the zinc and the platinum. A solution of potash, substituted for the acid solution, produces the same effect. If we introduce into the circuit the wire of a multiplier *g* (*fig.* 303.)*, the needle is immediately deviated, as well in the former as in the latter case. Mr. Faraday has obtained a very great number of similar results, in submitting several electrolytes to the decomposing action of the current, produced by various metals plunged into different liquids, into which also a plate of platinum was plunged, intended to connect the exciting liquid with the liquid to be decomposed, as in the experiments that we have just related, without there having been contact between the two metals. The following is a Table of these results, in which are inscribed in the same

* In *fig.* 303. a platinum wire is soldered to the zinc *z*, and this wire is united to that which sets out from the platinum, by means of the paper *c*, moistened with the electrolytic solution. This is the apparatus that has been employed in the experiments, whose results are contained in the following Table.

horizontal line the four substances comprised in the circuits; viz., 1st, the metal attacked; 2nd, the exciting liquid; 3rd, the metal not attacked or less attacked, which serves as a conductor; 4th, the electrolytic liquid, that is decomposed.

Iron.	Diluted nitric acid.	Platinum.	Sulphuret of potassium.	Decided current.
„	„	„	Red nitric acid.	„
„	„	„	Strong pale nitric acid.	Tolerable.
„	„	„	Green nitrous acid.	Very energetic.
„	„	„	Iodide of potassium.	Decided current.
„	Diluted sulphuric acid.	„	Sulphuret of potassium.	„
„	„	„	Red nitric acid.	Tolerable.
„	Muriatic acid.	„	Green nitrous acid.	Very energetic.
„	Diluted „	„	Red nitric acid.	Tolerable.
„	„	„	Sulphuret of potassium.	„
„	Solution of salt.	„	Green nitrous acid.	Very energetic.
„	Ordinary water.	„	„	Tolerable.
Zinc.	Diluted nitric acid.	„	Iodide of potassium.	„
„	Muriatic acid.	„	„	„
Cadmium.	Diluted nitric acid.	„	„	„
„	Muriatic acid.	„	„	„
Lead.	Diluted nitric acid.	„	„	„
„	Muriatic acid.	„	„	„
Copper.	Diluted nitric acid.	„	„	„
„	Muriatic acid.	„	„	„
Lead.	Strong sulphuric acid.	Iron.	Diluted sulphuric acid.	Strong.
Tin.	„	„	„	„
Copper.	Sulphuret of potassium.	„	Diluted nitric acid.	Energetic.
„	„	„	Iodide of potassium.	„
„	Strong nitric acid.	„	Diluted nitric acid.	Very energetic.
„	„	„	Iodide of potassium.	„
Silver.	„	„	Diluted nitric acid.	Strong.
„	„	„	Iodide of potassium.	Tolerable.
„	Sulphuret of potassium.	„	Diluted nitric acid.	Strong.
Tin.	Strong sulphuric acid.	Copper.	Diluted sulphuric acid.	„

Several philosophers, and especially Davy, had already shown that voltaic batteries might be formed with a single metal and two liquids; but they had never constructed a single pair, and the nature especially of these phenomena had never been elucidated.

In the Table, that we have transcribed above, we may remark, that the exciting liquid varies with the electrolytic liquid to be decomposed. Indeed, in order that decomposition may take place, it is necessary that the action of the former liquid upon the zinc should be more powerful than that of the latter, in order that the current, that results from it, may preponderate over the affinities of the electrolytic liquid and modify them. Thus we are unable to decompose water acidulated with sulphuric acid by means of a zinc and platinum pair, plunged into a similar acidulated water, whilst we decompose a solution of iodide of potassium and of melted chloride of silver.

A solution of soda, of hydrochloric acid, of nitrate of silver, melted iodide, and chloride of lead, resist this decomposing force; but they are decomposed if we add to the diluted sulphuric acid, which serves as the exciting liquid, a little nitric acid, which increases the chemical power of this liquid upon the zinc.

But we have already remarked, in reference to electricity liberated under the form of tension, that there was no relation between the vivacity of the chemical action, and the intensity of the electric signs to which it gives rise. The same observation is applicable to the electricity, produced under the form of current; it is rather the nature of the chemical action, than its vivacity, which influences the intensity of the electric manifestation. It does not follow from this, that the quantity of electricity liberated is not in relation with the quantity of chemical action, which takes place; on the contrary, we shall see further on, that these two quantities are exactly proportional to each other; but the faculty which this electricity possesses of surmounting a certain resistance, or what Faraday has called its *intensity*, a quality which must not be confounded with *quantity*, varies with the

nature of the chemical action, that takes place upon the attackable metal of the pair. We may further remark, that the greater or less proportion of the two electricities, that are immediately recomposed on the surface of the attacked metal, must necessarily be the inverse of that, which is transmitted through the circuit; and consequently with a given pair, must vary with the resistance of this circuit. However, this immediate neutralisation of the two electric principles, which Mr. Faraday has called *local action*, is due to another cause, that we must endeavour to analyse.

I had already remarked, as long ago as 1830, that perfectly pure distilled zinc, when plunged into diluted sulphuric acid, is scarcely attacked, especially in the first moments of its immersion, and even when the action has lasted for a tolerably long time, gives rise to only a small number of bubbles of hydrogen; whilst the ordinary zinc of commerce, placed under the same circumstances, produces an enormous quantity of hydrogen, which is liberated with effervescence. However, when united voltaically with platinum, the former zinc gives, for equal surfaces, a more powerful current, and consequently liberates more hydrogen on the platinum than the latter. The cause of this difference is due to the zinc of commerce always containing a small portion of cadmium and especially of iron, as is proved by chemical analysis. In fact, we have merely to mix directly a tenth or even less of iron in very fine powder, with distilled zinc, to render it capable of liberating as much and even more hydrogen than the zinc of commerce, when plunged into acidulated water. The phenomenon is therefore evidently electro-chemical; and what further proves it is, that the solution of sulphuric acid, which gives with zinc in which there is some iron, as with the zinc of commerce, the most abundant gaseous liberation, is the same as that, which has the most powerful conducting power for electricity; namely, the solution of the density, 1·259.

It is therefore evident that there is established upon the surface of zinc, which contains particles, either of iron or of a metal less oxidisable than zinc itself, currents arising from the numerous pairs, that are formed by the particles of

iron with the particles of zinc, that touch them. These currents decompose the water, that they traverse; the zinc oxidises and is dissolved in the state of sulphate; and the hydrogen is liberated, wherever there are some portions of iron in contact with the liquid. Mr. Sturgeon, on examining closely the surface of a plate of zinc, plunged in diluted sulphuric acid, proved the existence in it of these negative poles, which frequently changed their place during the continuance of the chemical action, on account of the deposition of oxide, of the texture of the metal, &c. The points, which serve as negative poles, suffering no alteration, we perceive why a plate of zinc becomes roughened after a long immersion in a liquid, that attacks it. Iron is not the only metal, whose presence in zinc produces this effect; copper, lead and even tin and cadmium, all less oxidisable than zinc, in like manner but in a less degree determine it; especially the two latter. We may even, by implanting artificially upon the surface of a piece of distilled zinc, a multitude of small points of platinum, produce a very considerable gaseous liberation, which takes place at the extremities of these points, when all these little pairs are plunged into the solution of sulphuric acid.* The same effect is produced upon cadmium, which, when pure and insulated, enjoys the same property as distilled zinc.

We may give to ordinary zinc the same property as distilled zinc, of being but little attacked, when plunged into water acidulated with sulphuric acid; for this purpose, we have merely to amalgamate its surface, an operation easily

* It is to a similar cause, that we may attribute the influence that, according to the observations of M. E. Millon, is exercised over the decomposition of water by zinc, by the presence in the acid or saline solution, in which the zinc is plunged, of small quantities of a metallic salt. Thus, the addition of a little bichloride of platinum to the diluted sulphuric acid causes a plate of zinc to lose in weight 66¼ grs., in the same time in which a similar plate in the same acid pure, would lose only ⅔ grs. It is evident, that a precipitation takes place of a little platinum upon certain points of the surface of the zinc, from which results the formation of voltaic pairs. And indeed the intensity of the effect varies with the nature of the metallic solution, and consequently of the metal deposited; thus, it is more powerful with bichloride of platinum than with sulphate of copper. Tin and iron present analogous phenomena to those offered by zinc. We may remark, that although all the effects observed by M. E. Millon cannot be explained exactly in the same manner, they are yet all due to electro-chemical causes.

done; for we have merely to rub the surface of the zinc with a rag, impregnated with a solution of sulphuric acid, in order to clean it, spreading mercury at the same time over this surface. Placed in contact with a plate of ordinary zinc in the acid solution, the plate of amalgamated zinc forms, like distilled zinc, a pair, of which it is also the oxidisable element; although, when it is isolated, it is scarcely attacked at all by the solution. But if we make it communicate with a wire or a plate of platinum, its zinc is rapidly dissolved, with a powerful liberation of hydrogen upon the platinum. Exactly the same effect takes place with distilled zinc. It is evident that this similitude of effects is due to the fact that the washing with diluted sulphuric acid, and the amalgamation that follows, causes to disappear from the surface of the zinc of commerce, all the impurities that are found mixed with it, such in particular as the small molecules of iron. In truth, there is brought about a true solution of pure zinc in the mercury, which covers as a liquid film the surface of the plate of zinc. Now, pure zinc, alloyed with mercury, can no more be attacked than isolated pure zinc can; for the mercury in this case does not form pairs with the molecules of zinc, as the particles of iron, that are simply disseminated in the metal and not alloyed with it, would do; the mercury here plays the part of a simple solvent. Only, as soon as, by its contact with the platinum, the amalgamated zinc forms a pair, the attraction of the mercury by the zinc is no longer more powerful than the cohesion, which retains the particles of simply distilled zinc to each other, in order to prevent the acidulated water from oxidising and dissolving the metal in this case as in the other. Faraday, who has made a great number of experiments upon this subject, has found that two plates of amalgamated zinc, placed each separately in a test-tube, filled with a solution of sulphuric acid, one of which was insulated, whilst the other was in contact with a plate of platinum, in the same time the former had scarcely lost any part of its weight, liberating very little hydrogen, whilst the latter had lost several grains, liberating an equivalent quantity of hydrogen upon the platinum.

But a much more important question presents itself here: how comes it that amalgamated zinc, or distilled zinc, which comes to the same thing, which are but little or not at all attacked by acidulated water, are so powerfully so, when they are united, by means of a conductor, with a metal that is but little or not at all oxidisable, plunged into the same liquid, and then give rise to a much more powerful current, than that which is produced, under the same circumstances, by the zinc of commerce so powerfully attacked?

We may first remark that the action, which the latter zinc suffers, cannot contribute to the formation of the current of the pair, since it arises simply from the superficial currents produced by the molecular pairs,—currents, that do not traverse the circuit. On the contrary, these currents, which consume zinc uselessly, diminish greatly the force of the principal current of the pair; and on this account it is that, for equal surfaces, a plate of amalgamated or of distilled zinc gives a more energetic current than a plate of the zinc of commerce; and is positive, in respect to this latter, when it forms a pair with it.

This point being established, we are able to consider, as a principle demonstrated by experiment, that a particle of zinc perfectly pure, presenting no trace of oxidation, is incapable of decomposing water, when it is placed isolately in a solution of sulphuric acid.* But if it is put in contact with a less oxidisable particle than itself, being a conductor, such as a particle of platinum, of iron, of copper, or even with a particle of its own oxide, the water is decomposed, and an electric current is produced. This current is, in this case, molecular; but its circuit is of a finite size, when, instead of two molecules, there are two wires or two plates in contact and forming an arc, which are in the same liquid. The production of the current is simultaneous with the chemical action; it is neither anterior nor posterior to it; it is not posterior to it, since there is no chemical action, without the formation of a pair; it is not anterior to it, since the current can be esta-

* M. d'Almeida, has lately confirmed this principle, by preparing, by the galvano-plastic method, zinc as pure as possible. The plate showed itself unattackable in sulphuric acid, diluted with only nine times its volume of water; and it required several hours for dissolving it in boiling acid.

blished only so long as the voltaic pair is charged with an electrolytic liquid, susceptible of attacking one of its metals, and not with any electrolytic liquid, however good a conductor it may be, as has been super-abundantly proved by the numerous experiments, that we have reported above.

It is to M. Schœnbein, who has found several voltaic combinations, in which chemical action does not pre-exist, as regards voltaic action, that we are indebted for the first idea of the theory, which accounts for these phenomena; a theory, which approximates much more closely to the manner in which Faraday regards them, and which is in accordance with what we have laid down on the electro-molecular constitution of bodies.

We will suppose, in what follows, that zinc and water are the matters in question; it is clear that the same would be the case for every metal and for every electrolytic liquid, of which one of the elements is susceptible of combining with this metal. When the zinc z is plunged into the water (*fig.* 304.),

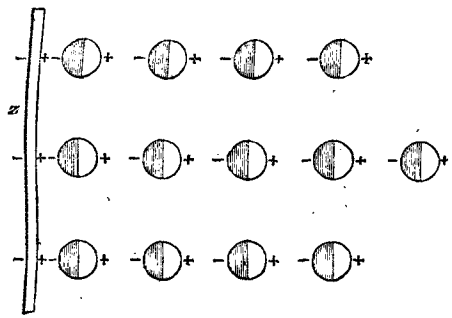


Fig. 304.

its molecules polarise each of the molecules of water, that touch it; these polarise the following; and so on, in such a manner, that there set out from the surface of the zinc as many filaments of molecules of water polarised, as there are points to the surface. Each of the molecules of these filaments presents its negative oxygen on the side of the zinc, and its positive hydrogen, on the other side; whilst the molecule of zinc has its positive electricity on the side, where it is in contact with the molecule of water, and its negative on the other.

This state of polarisation or tension ceases only at the moment when, on causing the zinc Z and the water to communicate with the ground, or with the plates of a condenser, which comes to the same thing, an escape is given to the negative electricity of the zinc, as well as to the positive of those particles of the water, that are in contact with the conductor, which may be the hand of the observer, or a plate of platinum P, which discharges them* (*fig.* 305.). At the same instant

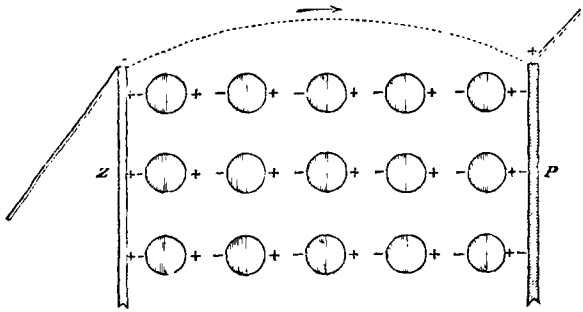


Fig. 305.

the oxygen of the particle of water in contact with the zinc, combines with it, giving rise to a neutralisation of their two contrary electricities; the hydrogen of this first particle of water combines with the oxygen of the second; and so on to the hydrogen of the particle in contact with the conductor P, which is liberated at the surface of this conductor. The same theory is applicable to the case of zinc, that contains heterogeneous substances, such as particles of iron. We may see (*fig.* 306.) the local currents, that are established upon the surface of the zinc, and which, setting out from the molecules of zinc, nearest to the particles of iron F, abut upon them, and here liberate hydrogen.

There are therefore four distinct but simultaneous phenomena, when we plunge into a vessel filled with water a plate of zinc, placed in communication with the plate of a condenser,

* The dotted line − +, represents a wire which unites the zinc and the platinum; the only difference between this case and the one upon which we are occupied, is that there is a continuous current instead of a succession of discharges; the oxidation also of the zinc and the polarisation of the platinum are obtained much more promptly.

and a plate of platinum in communication with the other plate of the same condenser, or with the ground: 1st, negative change, given to the plate that communicates with the zinc; 2nd, oxidation of the surface of the zinc; 3rd, liberation of hydrogen at the surface of the platinum; 4th, escape of positive electricity into the ground or into the plate, which communicates with the platinum.

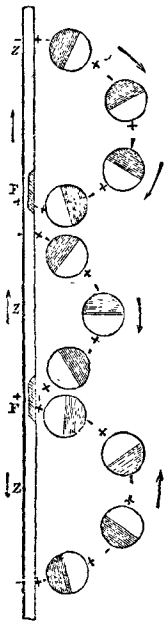


Fig. 306.

The quantity of chemical action, that corresponds to each charge of the condenser, is infinitely feeble; but on bringing about a great number of successive discharges, we end by perceiving the oxidation of the zinc, from the loss which it undergoes, but especially the presence of hydrogen, in that the plate of platinum is polarised. I have succeeded in proving this polarisation, by plunging into acidulated water two perfectly similar plates of platinum, and assuring myself by means of a very sensitive galvanometer, that they gave rise to no current; then I plunged into the liquid a plate of zinc, which I placed in communication with one of the plates of the condenser, whilst I caused one of the plates of platinum *a* to communicate with the other plate of the condenser, or with the ground, taking care that the second plate *b* remained insulated. After having thus discharged and recharged the condenser several times in succession, I connected respectively the two platinum plates with the two ends of the galvanometer, and I obtained a current, the direction of which indicated that the platinum plate *a* had been positively polarised, and consequently covered with a thin film of hydrogen. If it is the plate *b*, that communicates with the ground, or with the second plate of the condenser, and the plate *a*, that is insulated, it is the plate *b*, that is polarised positively.*

* This experiment, which I have several times repeated, always with success, proves that there can be no production, even of electricity of tension, in a voltaic pair, without there being a corresponding chemical action. I have succeeded, by making it under a slightly different form, in explaining a fact,

When the zinc is not pure the particles of the surface, where there is iron on any other substance less oxidisable than zinc, produce the same effect as platinum. The polarised filaments of water abut upon these points (*fig.* 306.), and there is there a liberation of hydrogen. It is these molecular currents, that constitute local action. It is probable that the

that M. Foucault had observed, and which he had conceived to be altogether favourable to the idea that liquids have for electricity a physical conductibility analogous to that of metals, independently of their electrolytic conductibility. The following is this fact: —

In a rectangular trough are arranged vertically, and at the equal distances of ⅔ in., eleven copper plates, enveloped with gold-beaters' skin or with filtering paper; on the edges of the box is placed a cross piece of wood, carrying six plates of amalgamated zinc, which are intercalated among the coppers. All these plates, copper and zinc, are separated, and communicate together only by the acidulated liquid, which is poured into the trough, and the level of which rises very little above the free edge of the copper plates; the zincs alone emerge by narrow prolongations, by which they are connected to their common support: finally, the two extreme coppers are placed in communication by the wire of a galvanometer. When the zincs occupy the middles of the cells, the galvanometer remains at 0°; but, as soon as the transverse piece suffers a displacement, in one direction or in to the other, the zincs are all brought together to the same side; and the result is a current, which goes from the coppers that are nearest to the zincs in the interior of the trough; and, consequently, from the most distant copper to that which is the nearest to it, outside of the trough. Now, it was easy for me to prove that this effect is only due to the fact, that these coppers are all polarised positively upon those of their faces, that are turned on the side of the nearest zinc. Indeed, if I take two plates of copper, or better still, two plates of platinum, and plunge them into the two extremities of a well insulated glass trough, filled with water very slightly acidulated, taking care that the conducting wires that come from these plates, are held by insulating handles, I obtain no current in the galvanometer, on making it communicate with these conducting wires when the plates are not polarised, even when I plunge between them a plate of zinc, also held by an insulating handle, whether I place the plate exactly between the two plates of platinum, or place it very near to one or to the other. If I cause the zinc plate to communicate with the ground, as well as the two plates of platinum, I have not yet any sensible current, so long as I place the zinc plate very accurately in the middle; but if I bring the zinc toward one of the platinum plates, I obtain one, in which this plate is positive. It is evident that, in this case, the negative electricity of the zinc, being discharged into the ground, the positive of the liquid escapes by the platinum plate that is nearest, liberating upon its surface the hydrogen, that arises from the electrolytic decomposition of the water. This slight film of hydrogen, by polarising the plate, renders it positive in respect to the more distant plate, which, on account of the greater extent of liquid, by which the zinc is separated from it, has not been able to serve for the discharge. In order to render the phenomenon more sensible, it is necessary to envelope the zinc in filtering paper, in order to be able to bring it as close as possible in the liquid, to one or other of the platinum plates, still avoiding metallic contact. It is a remarkable thing to see that it is merely necessary for the zinc plate or the two platinum plates to be insulated, in order to there being no longer any trace of current; only, it is essential to be sure, before each experiment, that the platinum plates are not polarised, and consequently do not act upon the galvanometer, when they are alone in the liquid.

chemical action, in many cases, of a liquid upon a metal, is brought about in this way; for when we are able to preserve the surface of a metal from all impurity, we have no chemical action, except with eminently oxidisable bodies, such as potassium.

We conceive that, when the zinc is sufficiently pure, either because it is distilled or by the effect of amalgamation, for no local action to take place, the number of particles which, for equal surfaces, serve for efficacious action, is much more great; which explains the superiority of pure over ordinary zinc, which we have mentioned above. This difference, very sensible for dynamic effects, is little or nothing for the effects of tension, which require but very little chemical action. This explains an apparent anomaly observed a long time ago by MM. Ampère and Becquerel, but pointed out latterly under a different and more striking form by M. Matteucci, from whom we borrow it. • A plate of amalgamated zinc with a surface of $\frac{1}{5}$ sq. in. is plunged into water slightly acidulated by sulphuric acid, and a plate of platinum in a similar solution separated from the former by merely a porous diaphragm. The former plate is in communication with the condenser; it gives no sign of tension, before the latter communicates with the ground; but, as soon as this communication is established, the gold leaves of the electroscope indicate a divergence of 10°. On repeating the experiment several times the same divergence is obtained; then, a platinum wire, which is in contact with the zinc plate, is plunged into the compartment, in which the platinum plate is; hydrogen is immediately liberated upon this wire, and yet the signs of tension are the same as before. Now, nothing else has been done than what a little local action would do; namely, a part of the zinc of the plate has been employed to produce a current, which results from the addition of the platinum wire; but more zinc remains than is necessary to supply the tension, and we should have the proof of this in the powerful current, that would be produced, notwithstanding the presence of the platinum wire, if the zinc was connected metallically with the platinum

plate. The result is the same, except with regard to the electric signs, which from negative becomes positive, when the platinum plate is made to communicate with the condenser, and the zinc plate, still united to the liquid, by the platinum wire, that is soldered to it, is made to communicate with the ground.

In the theory, that we have been laying down, we have admitted that the conductor, associated with the zinc, was altogether inactive, — that it was a plate of platinum. Things go on in the same manner if it is attackable by the liquid, if it is a plate of copper, or of iron for example; only the polarisation of the liquid, brought about by the zinc, is diminished in intensity by the force of the contrary polarisation, which is brought about by the chemical affinity of the oxygen of the water for the copper or for the iron. If the two polarisations are perfectly equal, it is clear that one destroys the other. But it may happen that the conducting substance associated with the zinc, instead of having affinity for oxygen, may have it for the hydrogen of the water, then the polarising force of the zinc upon the liquid filament, interposed between the conductor and itself, far from being diminished, is on the contrary increased; and the current acquires by this a much greater intensity. This happens, when the platinum plate is covered with a film of peroxide of lead, a substance whose affinity for the hydrogen of the water is very great, on account of its tendency to be de-oxidised. The negative electricity of the zinc plate, and the positive, that is acquired by the platinum plate, become much more powerful, as is proved by the charge of the condenser. I have even succeeded in obtaining by this combination a pair, capable of actively decomposing water acidulated by sulphuric acid in a voltameter with platinum wires. The peroxide, brought to the state of a dry and fine powder, is carefully rammed into a porous trough of unglazed porcelain, such as those, which are used in the Grove's piles. A thin plate of platinum is placed in the middle of the trough, so that it is completely enveloped by peroxide. This plate carries an appendix, to which is soldered a conducting wire. The porous trough, filled with peroxide and

a plate of amalgamated zinc, are plunged into a saline or acid solution; then the plates of zinc and platinum are made respectively to communicate with the two wires of a voltameter; by this means as much as $\frac{3}{5}$ cub. in. of the mixed gases are obtained in a minute, whilst with a similar Grove's pair, except that nitric acid is substituted for the peroxide of lead, a scarcely sensible decomposition is produced. Only, the effect is enfeebled at the end of a few moments, by the infiltration of a little sulphate of zinc into the peroxide and by the deoxidation of the peroxide itself. It is reduced more rapidly, and is much less intense, when peroxide of manganese is substituted for peroxide of lead, as I have proved. Yet in this case* $\frac{1}{10}$ cub. in. of gaseous mixture is obtained per second.

The tendency of the peroxides of lead and of manganese to deoxidise, borrowing hydrogen from the water, is so powerful, that we are able to obtain, both in the state of tension and in the state of current, very decided electric signs, by plunging into an acid solution, and even into pure water, a plate of platinum and these peroxides, either in pieces, or in the state of powder, spread upon a sheet of platinum; Schœnbein was the first to remark this. The polarity is here brought about by the negative element of the pair; the platinum plate gives to the condenser negative electricity, whilst the peroxide communicates to it positive electricity, and the current travels in a conductor, that unites these two substances exteriorly to the liquid, from the peroxide to the platinum; but this current can only be detected by its action upon the galvanometer; it is unable to traverse a voltameter of acidulated water, being incapable of decomposing water. Acid solutions, and especially those of hydrochloric acid, render the current much more energetic by facilitating deoxidation; M. Matteucci, by plunging into hydrochloric acid a platinum wire, covered with peroxide of lead, and a gold wire, forming a pair, obtained a very strong current, and the

* The surface of the platinum plate was about $15\frac{1}{2}$ in. square; that of the zinc was double, the plate of this latter metal being bent, in order to surround the porous trough, as in Grove's pile.

formation of a chloride of gold. There was no effect, when the platinum was not covered with the peroxide. If a piece of chromate of potash is substituted for the peroxide, a current is obtained of a very remarkable intensity, especially on employing as a liquid, interposed between the chromate and the platinum, hydrochloric or nitric acid; we know that there is a deoxidation of chromate of potash. M. Poggendorff has likewise observed, that a plate of copper, whose surface is oxidised, facilitates, like peroxide of lead, the production of the current, when it forms a pair with zinc in diluted sulphuric acid.

M. Becquerel had previously to myself obtained electric currents with a pair of platinum and peroxide of manganese; but he used only pure water, and did not employ other peroxides; he found that the effect is manifested, under the form of a species of discharge which requires, in order to its renewal, that the circuit be interrupted for several moments, and which is the more intense in proportion as this interruption has endured for a longer time. This result is probably due to the imperfect electric conductibility of the liquid employed, and the feeble chemical action, that it exercises. M. Becquerel had also produced effects of tension on the condenser, by touching it with a platinum plate, upon which was placed peroxide of manganese, held between the fingers; we shall see that this is due to the same cause.

M. Munck, on comparing in this respect various negative substances, had obtained the following results, which show the superiority of the peroxides, by causing the various substances, whose names follow, to communicate with the copper condenser, by means of a moistened paper, and which he touched with a plate of zinc, held between his fingers: —

Zinc placed in contact with	Degrees of negative tension.
Copper	4°
Silver	4½
Carbon	4⅔
Gold	5
Black sulphuret of mercury	5½
Pyrites	6
Peroxide of manganese	6½
Peroxide of lead	9½

As we shall see further on, the moisture of the hand performs for the zinc the part of water and tends consequently to give to it negative electricity, whilst the positive goes into the ground by the body of the observer. Copper, silver, carbon and gold only play the part of conductors, whilst the action of the moist paper upon the latter substances of the Table, adds its effect to that of the oxidation of the zinc, since this action tends to give to the paper, and consequently to the condenser, negative electricity. Moreover, we shall return to these rather complex phenomena, when we shall be examining the question of the development of electricity by contact.

It follows, from what precedes, that the production of electricity in a voltaic pair is only a manifestation, producing itself under a different form, of the electricity, that always accompanies a chemical action. Only under this form the electricity becomes perceptible directly; whilst, in the ordinary form, which we have designated under the name of local action, it is so only indirectly. Chemical affinity cannot therefore be exerted without there being at the same time a production of electricity, sometimes perceptible, at other times not perceptible. More than this: the formation of a pair, that facilitates the perception of electricity, favours in many cases the exercise of chemical affinity, particularly in the case, in which the homogeneity of the solid substance, exposed to the chemical action of a liquid, does not allow of the establishment of superficial molecular currents. It is by taking advantage of the new power, that is thus acquired by chemical affinity, and which he was the first to point out, that M. Becquerel succeeded in producing a great number of compounds hitherto unknown, and in obtaining in the crystalline state many substances, which they had never succeeded in crystallising before him. This order of facts, which is one of the most elegant applications of electricity to chemistry, will find its place in the Part of this Treatise which is devoted to Applications.

We may further remark, before quitting this subject, that metallic precipitations, such as those which are obtained in

the tinning of pins, or in plunging a plate of iron into a solution of sulphate of copper, are like the liberation of hydrogen by the action of diluted sulphuric acid upon the zinc of commerce, only an electro-chemical effect, due to molecular currents, that constitute what we have called local action. A plate of iron plunged into sulphate of copper almost always presents upon its surface one or two points slightly oxidised, where there are several flaws, perhaps some particles of carbon; this defect of homogeneity immediately brings about a small first current, which decomposes the sulphate; a little copper is immediately deposited; and then the action becomes only the more easy, until almost the whole of the surface of iron is covered with copper. It has in fact been remarked that, if this surface is perfectly homogeneous, which is difficult to obtain, the precipitation of copper no longer takes place. The important labours of Bucholz and Grotthus, and the more recent ones of Fischer and Breslau upon this subject, and in particular upon metallic vegetations, completely confirm the electro-chemical origin of this order of facts, the details of which enter into purely chemical phenomena, since the question is nothing more than the exercise of affinity. However, we shall be called to return to this, when we are engaged on the applications of electricity to chemistry.

It is also to a similar electro-chemical cause that we must attribute the important fact, observed for the first time by Davy, that a metal, copper for example, may be protected against the corrosion exerted upon it by an acid or a saline solution, such as sea-water, by associating it voltaically with a more oxidisable metal, such as zinc. There is produced between the zinc, soldered or applied to the copper, and the copper itself, a current that decomposes the water, and deposits its hydrogen against the copper surface; hydrogen, that prevents oxidation or destroys it in proportion as it takes place. In this latter case, which is very frequently presented, the copper finishes by becoming covered with a pulverulent powder. If the solution contain salts with an insoluble base, or one but little soluble, as is the case of sea-water, the

copper is soon seen to be covered with a basic earthy deposit.* It had been for a moment thought that the simple contact of copper or iron with a more oxidisable metal, such as zinc, would render them inattackable, because it constitutes them into a particular electrical state; but M. Schœnbein has demonstrated, by a numerous series of experiments, that iron and copper oxidise in air, in water and in a saline solution, as well when they are in contact with zinc, as when they are not so, if there is no electric current; but that, as soon as there is one established, the negative metal, namely, the one that receives the hydrogen, is no longer oxidised. The formation of a deposit, arising from the decomposition of the solution, explains also the fact observed by M. Van Beck, that a copper vessel filled with sea-water, after having been for forty-seven days connected voltaically, by means of a platinum wire, with a plate of iron, plunged into the same liquid, and having been thus preserved from all oxidation, continued to be so when the platinum wire that connected the copper to the iron had been broken; but the sea-water having been changed, which evidently caused the preservate film, deposited on the surface of the copper, to disappear, the latter recommenced to oxidise.

After having well established the theory of the voltaic pair, it remains for us to show how the intensity of the electricity to which it gives rise, may be reinforced. In order to render the explanation we are about to give more clear, we will designate, under the name of *electro-motive force* of a pair, the force with which the molecules of the electrolytic liquid, which enters into the formation of this pair, are polarised; a force, which depends, when the negative element of the pair is inactive (platinum and zinc), on the affinity alone of the positive element for one of the elements of the liquid; which depends, on the contrary, upon the affinity that is possessed for the other element of the liquid, by the negative element of the pair, when it is this which is active, and when the positive is not (platinum and peroxide of lead); and, finally, which depends

* The formation of this deposit has unfortunately rendered Davy's process, inapplicable to the preservation of the copper, that covers ships exteriorly.

upon the two affinities equally, when both the elements of the pair are active (zinc and peroxide of lead). Our definition of electro-motive force is very different from that which is given to it in Volta's theory, in which under this denomination is designated the force, with which it is supposed that, in the contact of two heterogeneous bodies (platinum and zinc), one is constituted into the negative state, and the other into the positive.

The electro-motive force of a pair, depending upon the affinity of its two elements for those of the electrolytic liquid, we may conceive that it must vary with the nature of these two elements, and with that of the liquid; whence there results a very considerable number of possible voltaic combinations. We will point out, at the end of this Chapter, the methods, that have been employed for measuring this force, and the application of them, that has been made to the measurement of the power of the different voltaic pairs. We shall endeavour to see, at the same time, to what point we are able, in the measuring of electro-motive force, to find a means of measuring the power itself of affinity. For the present, we shall confine ourselves to explaining how, a pair being given, we are able to increase its electro-motive force. For this exposition, we shall take as a type the most simple pair, namely, a pair formed of a plate of amalgamated zinc, and a plate of platinum, each with a surface of about $15\frac{1}{2}$ sq. in. plunged into water acidulated with sulphuric acid. We will suppose the liquid placed in a well-insulated glass vessel, and the two metal plates each furnished with an appendix of the same metal also well insulated (*fig.* 305.).

The electro-motive power of this pair may be appreciated either by the condensing electrometer, the electricity with which each of the metals of which it is composed being collected in the static state, or by a rheostat, this same electricity being manifested in the dynamic state, by its action upon a magnetic galvanometer. In order to increase the electro-motive force of the pair, that is to say, in order to have a greater tension detected by the electrometer, or a greater resistance surmounted in the rheostat, with the same devia-

tion of the galvanometer, it will be sufficient to place in succession to this former pair a second similar one, so that the platinum appendix of the former is in contact with the zinc appendix of the latter, and consequently that the zinc appendix of the former and the platinum appendix of the latter are insulated. On making these two appendices communicate respectively with the two plates of the condenser we shall have a tension the double of that, which we had with a single pair, and in making them communicate together by the wire of the galvanometer and by that of the rheostat, so as to close the circuit, we shall produce a current, that will surmount a resistance the double of that which the current of a single pair would have surmounted. With three pairs, arranged in like manner, one after the other, the tension in the static state will be triple; and the resistance surmounted in the dynamic state, will be triple also; and so on, in such sort that for n pairs the tension and the resistance would be n times greater.*

Now it is easy to comprehend why the addition of a second pair doubles the force, that polarises the successive molecule of the liquid, as well as that with which their combinations and recompositions are brought about, — why the addition of a third triples it, of a fourth quadruples it, and so on. Let us take the case of two pairs voltaically united, as we have pointed out above. If the zinc of the second pair did not exercise any action, that polarised its liquid, this zinc, in communication with the platinum of the first, would receive and would transmit to the liquid molecules in contact with it, a polarity equal to that, which it had received from the platinum; that is to say, that the first molecule of the water would have its negative oxygen, turned towards the + of the platinum and the liquid of each of the two pairs would be polarised in the same manner (*fig.* 307.). But the zinc of the second pair exercises upon

* We shall see, in a following paragraph, that the proportionality between the tension possessed in the static state, by the electricity produced by a certain electro-motive force, is proportional to the resistance, that it is able to surmount in the dynamic state. With regard to the relation, that exists between this tension or this resistance on the one hand, and the number of pairs on the other, we cannot appreciate the point, up to which it is rigorously exact, until we shall have been enabled to know, and consequently to eliminate, the circumstances that tend to disguise it.

its liquid a polarising action, similar to that of the first. These two actions are evidently added to each other, since

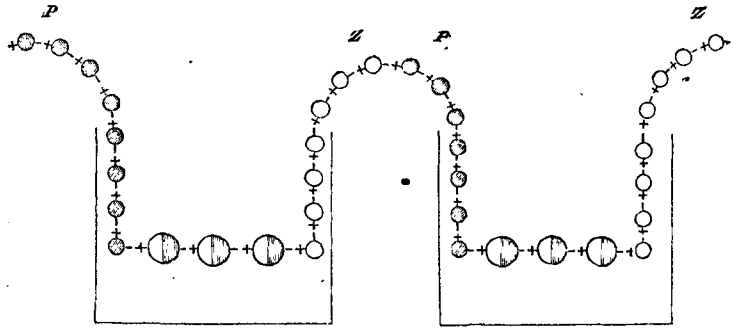


Fig. 307.

they take place in the same direction. Moreover, in its turn, the polarising action of this zinc is transmitted to the platinum of the first pair, with which it is in contact, and thence to the liquid and to the zinc of this pair, so that the two pairs have equally their electro-motive force doubled. In the same manner will be explained why the addition of a third pair will triple the polarising force; and consequently the electro-motive force of the three pairs equally; and why if there are n pairs these forces will be rendered n times greater.

Thus, when we have an insulated pile, composed of any given number of similar pairs, at the moment when its two poles are made to communicate with the two plates of a condenser, or with the ground, a chemical action is brought about, which is accompanied by a liberation of electricity. If the pile is composed of a very great number of pairs, the electro-motive force becomes sufficiently powerful for the chemical action to take place even when the poles remain insulated; thus, on making each of them communicate with an electroscope, we obtain, without the assistance of a condenser, the divergence of the gold leaves. The electric tension, that is acquired by each pole, depends, not only upon the intensity of the electro-motive force, but upon the more or less imperfect conductibility of the pile itself. Indeed, the two electricities accumulated respectively at each of the poles tend to reunite by the pile

itself, which separates them, and which plays the part of a simple conductor. Experiment, in fact, teaches us that this reunion is brought about here, as in an ordinary conductor*; that is to say, that, setting out from the two poles, where they have their maximum of tension, each of the two electricities goes on diminishing in force to the middle of the pile, where the electric state is zero. The contrary electricities, with which the two halves of the pile are charged, are not able to reach the intermediate pairs, since there is always, in each of them, a neutralisation of the two electric principles; they come evidently from the extremities, or the poles of the pile, where they are constantly renewed. The tension of the two poles would be the greatest possible if we could reconcile, with a great electro-motive force, a very imperfect conductibility of the pile; this is realised with dry piles, as we shall see in the paragraph devoted to the study of that species of pile.

In a series of experiments, that I had undertaken with piles charged either with pure water or with saline or acid solutions, I satisfied myself that, in order to obtain the maximum tension, it required a time long in proportion as the liquid was a less good conductor; and that it was instantaneously obtained with very good conducting liquids, such as acids diluted with water. Mr. Gassiot†, in a series of very remarkable researches made with his water-battery, composed of 3520 pairs of zinc and copper, perfectly well insulated, arrived thence at results, perfectly in accordance with the theory, that we have been laying down. He concluded, from his experiments, that the static effects of the pile exist previous to the closing of the circuit; and that this latter may be closed, when the tension is powerful, by a succession of sparks, which are established between two polar metallic surfaces, very near to each other. He has also observed that, in a pile, such as the water pile, in which the chemical action is not exercised without difficulty, the tension is produced but slowly; but he succeeded in proving

* For the manner in which electricity is distributed in a conductor that connects the two poles of a pile, *vide* Vol. II. p. 94. and following pages.

† Mr. Gassiot was assisted in his researches by Mr. C. V. Walker, who is well known for his works on electro-chemistry.

plainly that the static effects, as well as the dynamic effects, can be produced only so long as the chemical elements, which enter into the formation of the pile, are susceptible of combining together chemically. He likewise found that the more the mutual affinity of these elements is powerful, the less necessary it is, in order to produce great effects of tension, that the number of pairs be considerable. Thus he obtained with a pile composed of 100 well insulated Grove's pairs a tension at the two poles, as decided as with the water pile of 3520 pairs; and, in particular, sparks between two discs of copper each placed in communication with one of the poles, and placed at a distance of $\frac{1}{1000}$ of an inch from each other.*

It remains therefore well established that, in a pile, or in a pair, all manifestation of electric signs, as well under the static as under the dynamic form, is accompanied by a corresponding chemical action. This action is excessively feeble for a single discharge; but it becomes sensible, when a succession of discharges are brought about, as was done by Gassiot, by producing a series of sparks between the two poles of the water pile. It is especially sensible, when, connecting the poles of the pile by a good conductor, the succession of discharges are caused to be brought about with sufficient rapidity for constituting the current. We are then able not only to detect, but even to measure exactly, this chemical action; and it is found at once the same in each pair, and equivalent for each of the pairs, to what it is, exteriorly to the pile, in an electrolyte placed between the poles. It is this that we have still to demonstrate, in order to complete the exposition of our theory.

It is at first very evident that, in a single pair, zinc and

* Mr Gassiot even succeeded in obtaining signs of tension, by means of a very sensitive gold-leaf electroscope, with a single pair of Grove's, well insulated. The foundation of the difficulty that is encountered in obtaining very marked signs of electricity, arises from the pairs not being sufficiently well insulated, which is not at all times easy, especially when we are concerned with piles, charged like Grove's, with acids. Also it is by means of a peculiar construction, and by employing glass vessels alone, for containing the acid solution, that Gassiot succeeded in obtaining with 100 pairs of Grove's, the same effect as with his water battery.

platinum, the quantity of hydrogen, liberated upon the platinum, must be exactly equivalent to the loss in weight of the zinc, at least if there is no local action upon this metal; if there is any, we must take account of the hydrogen liberated on the surface of the zinc. Faraday, by accurate measurements and weights, has proved this essential point. If, instead of a pair, we have a pile, composed of a series of pairs, amalgamated * zinc and platinum, so arranged that the hydrogen gas, liberated by the platinum, can be exactly measured, and the zinc can easily be removed for weighing, we find that the quantity of hydrogen is exactly the same in each pair, and in a voltameter placed in the circuit, and that it is at the same time equivalent to the zinc consumed, that consequently the latter is also to the oxygen of the voltameter.

In order to make this last experiment well, each pair (*fig.* 308.) is constructed by means of a glass bottle, filled

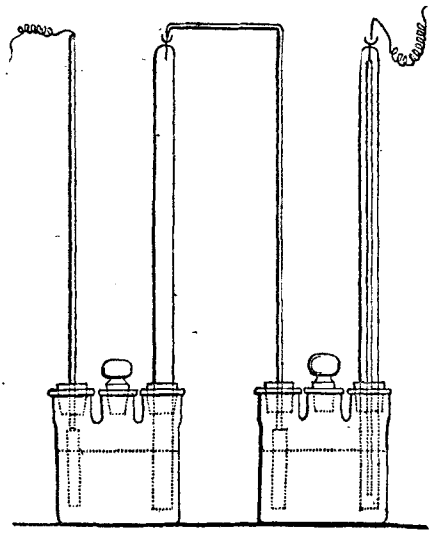


Fig. 308.

with a solution of very pure sulphuric acid. This bottle is

* The zinc must be well amalgamated, in order to avoid all local action.

pierced by three openings; one in the centre, closed by a glass stopper, by which the liquid is introduced; the other two on each side of the central one, one serving to introduce the amalgamated zinc, the other intended to receive very tightly a graduated tube, open below, and closed above, which is filled with liquid, and in which is placed a wire or a plate of platinum, the upper extremity of which comes out through the top of the tube, terminating by a clip or by a small metal cup, filled with mercury. Several similar pairs are arranged one after the other, care being taken that the wires, soldered to the zincs, arrive at the platinum of each consecutive pair. The circuit is then closed with any conductor, for example, with a voltameter; and when the action has lasted for some time, the hydrogen gas is measured in each pair, and in the voltameter, and the zincs are weighed. The accuracy of the law, that we have laid down, is thus proved. In order to prove it with a single pair, we have merely (*fig.* 309.) to make the zinc and platinum of the same pair communicate.

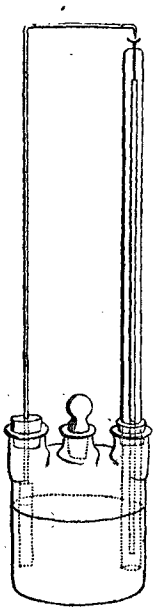


Fig. 309.

Any electrolyte, such as a metallic salt, may be substituted in the circuit for the acidulated water of the voltameter; and we always find that the reduced metal is equivalent to the hydrogen of each pair. We may also add that the law of equivalents for the pairs of a pile had been pointed out for the first time, after that Faraday had proved it for single ones, by M. Matteucci, who had proved it, by employing salts of copper and silver for determining the electro-chemical equivalents.

Thus then, when the poles of a pile are connected by an electrolyte, the quantity of effect produced in this electrolyte is equivalent to the chemical action, or to the chemical expense, that takes place in each pair. If the pile has, for example, ten pairs, ten equivalents of zinc must be consumed, in order to decompose one equivalent of water; twenty, when there are

twenty pairs. It would seem, therefore, much more advantageous to employ only one or two pairs; since, in order to produce the same effect, we should expend twenty or ten times less zinc. But, besides that the decomposition would be much less rapid, which would present grave inconveniences in many cases, there are a great number of electrolytes, which can be decomposed only so long as the current possesses a certain intensity; or, which comes to the same thing, that the electro-motive force possesses a certain power, which can only be given to it by multiplying the number of pairs. It is the same for the resistances, that are to be surmounted. Thus, when a current is called upon to traverse a very long telegraphic wire, it is necessary for it to be produced by a pile of numerous pairs (which occasions a greater expense of zinc); because, if it were produced by only one or two pairs, it would not have sufficient intensity to overcome the resistance of the wire.

However, there exists a manner of increasing the electromotive force of a pair, and consequently the intensity of its current, without its being necessary to add to it a second or a third pair; it is to cause it to be traversed by an induction current, guided in the same direction as the current itself of the pair. This induction current which, when alone, would decompose water, adds its effect to that of the pair, increasing its polarising force, and facilitating the decomposition and recomposition of the successive molecules of the water. I have already described an apparatus, that I have constructed for this object* in which it is the pair itself that produces the induced current, the effect of which must be to increase its own force; and I have shown that a pair, which could not decompose water in a sensible manner, becomes by this artifice capable of giving to a voltameter of platinum wires, charged with sulphuric acid to a tenth, as much as three cubic inches of mixed gases per minute. It is true that no economy of zinc is produced; for, besides that which is consumed at the moment, when the current circulates through the voltameter, and which is equivalent to

* Vol. I. p. 385. *fig.* 148.

the water decomposed, a certain quantity is expended at the moment when the current of the pair, instead of traversing the voltameter, passes through the wire of the bobbin, in order to produce the magnetisation, which gives rise to the induction. This expense might be avoided by developing the induction by means of a magnet; but then a mechanical force would be necessary, in order to bring about the rotation of the induction apparatus. This would, it is true, be more economical, since we should only expend a quantity of zinc, equivalent to the chemical effect obtained; but in a mechanical point of view, we should always have need of a force, equivalent in its effect, although of a very different nature to that which the zinc, that had been economised, might have produced. Moreover, more time would be necessary, in order to obtain the same chemical result.

To sum up, it follows from the analysis, that we have been making, that the law of electro-chemical equivalents discovered by Faraday, and which we have laid down at first, as far as it concerns the decomposition of electrolytes placed in the circuit exterior to the pile *, is general, and is equally well applied to what takes place in the interior itself of the pile as on the outside. We may therefore consider the circuit of a pile, when it is closed, as a system of conductors united end to end, in the series of which the current circulates in a manner perfectly uniform and identical; — circulation, which is brought about by a succession of polarisations and recompositions of the contrary electricities of the consecutive molecules, in such sort that this operation is accompanied by a liberation of heat when it encounters a certain resistance, and of chemical decompositions, when the molecules are compound. But all these effects are equivalent in all the parts of a same circuit, the pile included; we have just proved it, as far as chemical effects are concerned, and we have already seen that it was the same for the effects of heat.†

It would remain for us to examine what the influence is of the number of the pairs upon the effects, that require a great

* Vol. II. p. 352 and following pages.
† Vol. II. p. 250.

rapidity in the circulation of the current, such as the effects of heat, as well as the modification that is produced in a pile, by the introduction of one or more pairs more powerful or more feeble than the others, or simply that of homogeneous metallic diaphragms, or inactive pairs. The influence of these circumstances, and of several others, which it is useless to enumerate here, depend upon causes which we cannot appreciate until after we have finished the study of the liberation of electricity in the different forms under which chemical action is exerted. It is not until the end of this Chapter, that we shall be able to appreciate them. This we shall do in the paragraph, in which we shall compare the different species of piles with each other, with regard to their powers, considered under different relations. We shall then see also the part played by the extent of the surface of the pairs;—a part, moreover, that may be easily comprehended even now; for the size of the surface, being able to influence only the quantity of chemical action, exerted in a given time, it can in no way modify the electro-motive force of the pair or the pile, nor consequently the faculty of the current produced for surmounting this resistance. We may remark merely, that this resistance, when it exceeds a certain point, itself limits the quantity of efficacious chemical action by the quantity of electricity that can be transmitted in a given time, and consequently renders useless an augmentation of the surface beyond a certain size; a size which is itself in relation with that of the resistance.

Production of Electricity by the Chemical Action of Solutions upon each other.

M. Becquerel is the first philosopher, who has shown that, on causing two solutions, that are conductors of electricity, to act upon each other, and which are capable of mutually exercising a chemical action upon each other, however feeble it may be, an electric manifestation is obtained under the form of a current. In order to observe this effect, the two extremities of a good galvanometer are made to communicate

(*fig.* 310.) respectively with two plates of very well cleaned platinum, which are plunged, one into a glass *d*, filled with

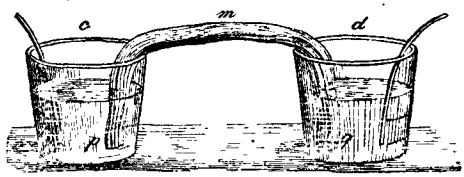


Fig. 310.

nitric acid, the other into a glass *c*, filled with a solution of potash, for example; the two liquids are then connected by a skein of cotton *p m q*, or better still of amianthus moistened by water slightly acid or salt. There is immediately a production of a current, which goes from the potash to the acid through the skein; and consequently from the platinum plate, which is plunged into the acid, to that which is plunged into the potash, through the galvanometer. Davy having attributed the production of electricity, in the experiment that we have been relating, to the contact of the platinum with the nitric acid on the one side, and with the potash on the other, M. Nobili showed, contrary to the result obtained by Davy, who had employed too sensitive a galvanometer, that a decided current may be obtained by avoiding the contact of the platinum with the acid and the alkali. In order therefore to escape this objection, it is necessary slightly to modify the arrangement of this experiment of M. Becquerel's; in consequence, the two platinum plates of the galvanometer are made to plunge into two capsules, both filled with a solution of nitrate of potash; then, by means of a skein of amianthus, the two capsules are made to communicate respectively, one with the nitric acid, the other with the solution of potash; the acid and the potash being also placed in communication by means of a similar skein, a current analogous to the preceding is obtained, but more feeble, on account of the imperfect conductibility of the nitrate of potash, and of a particular influence, that results from the contact of the nitric acid with the negative plate of platinum, of which we shall speak further on. MM. Nobili and Becquerel have also suc-

ceeded in obtaining this current, by substituting a piece of caustic potash for the solution of potash: the former, on plunging the piece of potash into the acid, after having fixed it to the extremity of the skein of cotton, the other extremity of which plunges into one of the vessels filled with nitrate of potash; the latter, by taking a platinum spoon, filled with nitric acid, and plunging into it the potash, held by platinum pincers, the spoon and the pincers being placed respectively in communication with the two ends of the galvanometer wire.

In order to avoid every objection, M. Becquerel has likewise operated, in another manner, by which the contact of the platinum with the different substances is also avoided. He plunges the two platinum plates of the galvanometer into two glasses, each of them filled in like manner with nitric acid; then, he causes them to communicate by means of a skein of cotton saturated with water, and about four inches in length, taking the precaution, on account of its length, of supporting it by a glass tube; about the middle of this skein, a drop of acid and a drop of dissolved potash are placed gently with a tube beside each other. So long as the two drops are separated, there is no effect; but at the instant when their reunion takes place, there is the production of an electric current, going directly from the potash to the acid, and from the acid to the potash, through the circuit. By substituting other acids for nitric acid, the results are the same; but more or less decided, according to the energy of the chemical action, and the conductibility of the liquids.

Instead of water, we may employ a saturated solution of nitrate of potash, or of any other salt, such as sulphate of soda, for moistening the skein of cotton or amianthus. In this case, the acid and the alkali, in which the extremities of the skein are plunged, exercise upon them chemical actions, which give rise to currents, more feeble than that which results from the action of the acid and the alkali upon each other, but moving in the same direction. These partial currents are the only ones, that are manifested at the very moment, when the union of the acid and the alkali is

brought about by means of the skein. Thus the effect is more feeble; but, at the end of a few moments, if the skein is not too long, there is an infiltration of the acid and the alkali, which, finishing by meeting each other, combine in considerably strengthening the current. Thus nitric acid and potash, united by a skein impregnated by sulphate of soda; having at the commencement given a constant deviation of only 4° or 5°, at the end of a few moments, give an equally constant current of 20°, which corresponds with a force at least eight or ten times greater. The former deviation was evidently the results of currents, arising from the respective chemical actions of the acid and the alkali upon the sulphate of soda of the skein; and the latter, from the additions to these currents of that which would be produced by the direct action of the acid upon the alkali. The current due to the action exercised over the solution, with which the skein is impregnated, vary with the nature of this solution and of the liquids, into which the extremities of this skein are plunged. Still more decided effects are obtained, by moistening the skein with the solution of a salt, the acid and the base of which are the same as the acids and bases of the solutions into which its extremities are plunged; for example, a solution of nitrate of potash with nitric acid and potash; which proves that, even, in this case, there is still a chemical action, probably due to the effect of the mass or to the degree of concentration of the solutions.

The chemical action of acids upon acids may in like manner give rise to electric currents. Thus, if we pour into one of the branches of a tube bent into a U (*fig.* 311.) some concentrated sulphuric acid, and, into the other, some nitric acid, so that the two liquids touch at *m*, without mixing, which is easily obtained, on account of their difference of density, on plunging the platinum extremities *a* and *b* of the galvanometer respectively,

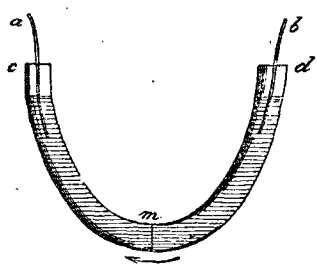


Fig. 311.

into the two acids, a current is obtained, which goes directly from the nitric acid *d*, to the sulphuric *c*, the former acid playing the part of base in respect to the latter. Phosphoric acid produces with nitric acid the same effect as sulphuric; and, opposed to sulphuric, plays the same part as sulphuric opposed to nitric.

The following is the order, in which the various conducting solutions may be placed, so that each shall be negative in respect to those which follow, and positive with those, which precede * : —

Phosphoric acid, sulphuric acid, nitric acid, hydrochloric acid, acetic acid, nitrous acid, saline solutions, alkaline solutions.

There are however cases in which saline solutions are negative with certain acids, and positive with certain bases; but these are exceptions, which are due to the circumstance, that the phenomenon is complex. We may remark that, in general, water plays the part of a base with acids, and of an acid with bases. It is probably on account of the considerable affinity that phosphoric and sulphuric acids have for it, whence it follows that they take it from other solutions, that we must attribute the fact that these acids are at the head of liquids in the above Table.

We may add that, in order to study thus the currents that arise from the mutual action of various solutions, it is preferable to have recourse to the first mode of operating (*fig.* 310.), by connecting the two liquids, into which the two platinum plates are plunged, by a skein of amianthus. It is necessary, at the same time, before each experiment, always to take the precaution of well cleaning the platinum plates by heating them to redness, then placing them in boiling nitric acid, and finally washing them in distilled water; then, having lone this, we assure ourselves, by plunging them into the same liquid, into nitric acid for example, that

* We always call that body (liquid in this case) positive, whence the currents or positive electricity sets out, in order to go directly to that, which acts chemically upon it, and from the latter to return to the former, through the galvanometer.

they produce no currents; which proves that their surface is quite clean. Notwithstanding this precaution, it always happens that, as soon as a current has been produced, by a chemical action, however slight it may be, the plates of platinum are polarised by the effect of gaseous or other deposits, arising from the chemical effects of the current upon the liquids, that it traverses; and that this polarity, which we have termed secondary, tends to produce a current, the converse of that, which has produced it. It follows from this that the intensity of the principal current is powerfully reduced by it, and sometimes even, to such an extent, that the current is no longer sensible.

In order to avoid this grave inconvenience, M. Becquerel has devised an apparatus, which he calls a *depolariser*, and which consists of an arrangement of conductors, which are caused to fulfil the office of rheotomes or of commutators. By this artifice, which, by means of a rotatory motion, combined with a downward and an upward motion, causes each of the plates of platinum to come at once out of the solution, in which it is plunged, in order to plunge it into the other, these plates are placed alternately in communication with one and with the other of the two solutions, still remaining connected respectively with the same end of the galvanometer, which causes the deviation of the needle always to take place in the same direction. In this manner, the current, due to the polarisation of the plates, is added to that which is due to the chemical reaction of the two liquids, in place of diminishing or destroying it. If the interrupting apparatus travels rapidly, and the current that is produced by the action of the two solutions, is constant, the deviation of the needle suffers no variation, whilst the platinum plates are in motion.

With the depolarising apparatus, we are able to discover sources of electricity in the slightest chemical actions, such as those, for example, that are produced by the reaction of distilled water, upon various solutions. Thus, on placing between the two glasses, in which the two platinum plates of the depolarising apparatus are plunged, a succession of four skeins of cotton, placed in contact one after the other, the

first and last of which are impregnated with distilled water, whilst the second is impregnated with water saturated with subcarbonate of soda, and the third with water saturated with bicarbonate of soda, a current is obtained in this circuit, which goes directly from the subcarbonate to the water. This current is the difference between currents going in contrary directions; indeed, between the water and the subcarbonate, there is a current going from the saline solution to the water; between the bicarbonate and the water, it goes from the water to the bicarbonate; and between the bicarbonate and the subcarbonate, it goes from the bicarbonate to the subcarbonate. Experiment shows that the sum of the two latter, the inverse of the former, is less powerful than it.

It is to an effect of the same kind that must be attributed the development of electricity obtained by M. Foucault in the following series of moist conductors in contact: *water, sulphuric acid, potash, water, sulphuric acid, potash, water, &c.* There are three chemical actions, which give three currents, directed, 1st, *water and sulphuric acid,* from the water to the acid; 2nd, *sulphuric acid and potash,* from the potash to the acid; 3rd, *potash and water,* from the potash to the water. M. Foucault's experiments only demonstrate, that the first and third currents, moving in the same direction, overpower the second, moving in the contrary direction; and cannot furnish the proof, as this philosopher had believed, of a physical conductibility proper to liquids.

We can therefore form piles composed simply of two liquids, reacting upon each other, and of a single metal, serving as the arc of communication between the different liquids of two consecutive pairs. The liquids, intended to act upon each other, are generally separated by a porous diaphragm, either of earth or of an organic tissue. There are cases, in which the difference of density between the two liquids enables of their being placed in contact, by simply superposing one upon the other, as we have seen above, when we showed the action of nitric acid and even of diluted sulphuric acid upon concentrated sulphuric acid. It is by

operating in the same manner that Berzelius had constructed a pile, in which a certain number of glass cups *a*, *b*, *c*, *d* (*fig.* 312.), were half filled with a concentrated solution of hydrochlorate of lime, and half with a stratum of diluted nitric

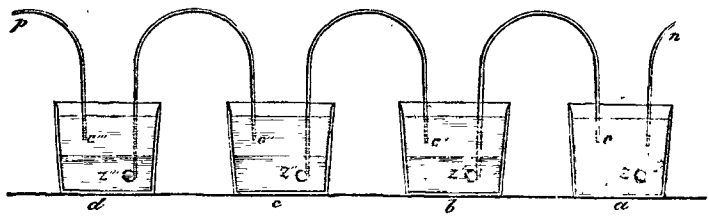


Fig. 312.

acid, which, being lighter, did not mix with the saline solution. Arcs of copper *c*, *c'*, *c''*, *c'''*, terminated at their extremities by little pieces of zinc *z*, *z'*, *z''*, *z'''*, were employed for connecting the cups; being arranged in such a manner, that the zinc extremity of each plunged entirely into the solution of hydrochlorate of lime, and the copper extremity into the upper stratum of acid in the following cup. In this pile, the zinc, although feebly attacked, is positive in respect to the copper, which suffers a very active chemical action on the part of the acid; and the more so, as soon as the circuit is closed, the zincs which had remained perfectly clean and brilliant in the saline solution, lose their brilliancy and become oxidised, whilst the coppers cease to be attacked. Although, in the chemical theory of the pile, as we have laid it down, this experiment is not an objection against that theory, since it is the nature much more than the vivacity of the chemical action, which determines the direction of the current, yet the effect in this case is especially due to the mutual chemical action of the two liquids; and the oxidation of the zinc, as well as the reduction of the oxidised copper, are only the results of the transmission through these metals of the current, arising from this action. Indeed, the same current is obtained by substituting homogeneous arcs of zinc, copper, or platinum for the metallic arcs zinc and copper: only the current is more powerful with arcs of zinc than with

arcs of copper or of platinum, and even than with the heterogeneous arcs of copper and zinc; which arises from its experiencing a much greater facility of passing from a liquid into a metal, in proportion as this metal is more oxidisable.

M. Nobili, who was one of the first, who made a detailed study of the currents, produced by the action of solutions upon each other, by employing either a galvanometer or a frog as a galvanoscope, had obtained electrical effects by causing acids to act upon salts, formed with the same acids, such as sulphuric acid upon sulphates, nitric acid upon nitrates, &c. In the double decompositions, the current is more frequently null, or at least very feeble.

Among the methods that have been proposed for determining the electricity developed in the chemical reaction of two liquids upon each other, we shall in addition point out that of M. Mousson, which consists in taking two discs, of about two inches in diameter, of platinum and silver, which he puts in metallic communication with the two ends of the wire of a galvanometer. He then applies respectively on these two discs, two discs of the same diameter, of unsized paper, moistened with the liquids, upon which he desires to operate; the two discs are then approximated parallelly, and are placed with pressure against each other. The deviation of the needle immediately indicates the existence and the intensity of the current. Although the galvanometer employed by M. Mousson was by no means sensitive, the effects observed were very decisive. Thus, with nitric acid and potash, the needle flew round and round several times; with potash and nitrate of potash, it deviated to nearly 80°; but in this case the effect is due to the reaction of the potash upon the water, which, it is true, when produced directly, gives only a deviation of from 25° to 30°, on account of the defect of conductibility: ammonia and pure water give 30°; nitric acid and water 90°. Sulphuric and hydrochloric acids present numerous anomalies in the electricity, that results from their action upon water, and even upon certain other solutions; which is probably due for the former to the effects of the heat liberated, and for the latter to the circumstance that the

chlorine must act upon the metals employed as electrodes. The effects of nitric acid are more regular.

We have now seen that solutions are able to act upon each other, so as to give rise to electric effects, which indicate that true chemical combinations are brought about; but sometimes there is only simple solution and not combination. Now, it is not always easy to distinguish which of the two phenomena it is that takes place, when the reactions are too feeble for our being able to find traces of new compounds, or to perceive an elevation of temperature. M. Peltier, in order to resolve this question, makes use of two platinum capsules, one filled with distilled water, and the other with the solution that is to be examined; he then joins them with a skein of cotton or amianthus, taking care to cause the two capsules to communicate with the extremities of a galvanometer with a long wire. If the body, whose action upon water, we desire to recognise, is solid, pincers of platinum are substituted for the capsule, between the branches of which it is placed; a thermo-electric tripod, composed of three pairs of bismuth and antimony, the lower extremities of which are of even or uneven orders, receives the capsule, in which the water is contained. If there is combination, at the moment when the two capsules, being connected, solution takes place, a heating is brought about, which is detected by a short wire galvanometer, connected with the thermo-electric tripod; and there is at the same time a deviation of the long wire galvanometer, which indicates the current, due to the chemical action. If, on the contrary, there is simply solution, this effect is indicated by reduction of temperature of the capsule, which gives rise to a thermo-electric current, moving in the inverse direction to the former. The direction of the thermo-electric current is sufficient therefore to show whether there is combination or solution, even when the variations of temperature, that result from it are excessively feeble. M. Peltier has consigned to a table, a very great number of experiments indicating in galvanometric degrees, the heat or the cold produced by the action of water upon different solutions, as well as the direction of the current, arising from their chemical action; a current, which is even never completely

null, in the case wherein cold is produced; but which is then very feeble. We shall not here reproduce this table; but shall confine ourselves to remarking that the greatest heat is obtained with sulphuric acid, potash, soda, lime; and the greatest cold with nitrate and hydrochlorate of ammonia, iodide of potassium, subcarbonate of potash, sulphate of zinc, as well as with boric, oxalic, citric acids, &c. &c.

Let us return for a moment to the reaction of nitric acid upon potash, seeing that the study of this kind of action has led M. Becquerel to the construction of a very simple apparatus, and one, moreover, very curious in its effect. This apparatus has received the name of the *oxygen-gas pile*, on account of the production of the gas upon one of the plates of platinum that enter into its construction. It is constructed in the following manner (*fig.* 313.): C D is a glass jar, filled with nitric acid, and in which is plunged a tube A B, maintained in the neck by a cork. This tube is closed at B, by means of a piece of linen; then by a certain quantity of clay or kaolin, kneaded into a thick paste, so as to occupy a thickness of about $\frac{1}{2}$ in. A small quantity of moist cotton, which is introduced into the tube at the extremity A, prevents the mixture of the clay with the liquid, that A B is to contain. In this tube is placed an aqueous solution of potash. The nitric acid of the flask and the solution of potash of the tube are therefore presented to each other by the intervention of the moist clay, as they were by means of the cotton in the preceding experiments. On then plunging two platinum plates P and N, one into the flask, the other into the tube, if these plates are in connection with a multiplier, there results an energetic electric current, in a direction such that the acid acquires positive electricity and the alkali negative. But this is not all; if the two plates P and N are connected by means of a single wire, we immediately perceive a multitude of small bubbles of gas produced around P in the potash; this gas is pure oxygen. It is liberated for

Fig. 313.

several days, as long as the pair acts. The effect is easy of explanation; the circulation of electricity due to the reaction of the two liquids, is established in the pair itself; the current sets out from the plate P, traverses the two liquids to go to the plate N, and to return exteriorly from N to P; the water of the solution of potash is decomposed, the oxygen is liberated on the plate P, and the hydrogen is transported into the nitric acid. The latter absorbs the nascent hydrogen, and is gradually coloured, in consequence of the presence of nitrous vapours.

The pair devised by M. Becquerel is the first with a constant current that had been constructed. This circumstance is due to the plates not being polarised, because the nitrate of potash that is formed is immediately decomposed by the current, and the acid and alkali, transported one to the plate P, the other to the plate N, are found in contact, the former with the potash, the latter with the nitric acid, which causes them to combine immediately and not to remain upon the plates. We may strengthen this pair considerably by substituting for the platinum plate that is plunged into the potash, a plate of amalgamated zinc; this plate, by seizing upon the oxygen, produces a current, which is added to the former. By means of this pair, thus modified, a powerful decomposition is obtained of acidulated water, placed in a voltameter with platinum wires. We may also connect voltaically, one after the other, several of Becquerel's pairs, so as to obtain a very powerful pile.

The oxygen-gas pile has been the subject of examination to several physicists, both in regard to its effects, and in respect to the nature of the action, which gives rise to the electricity, that it liberates. Thus M. Jacobi has succeeded in decomposing iodide of potassium by interposing it exteriorly between two platinum wires, soldered respectively to two plates of the same metals, plunged, one in nitric acid, and the other potash. He did not succeed in decomposing sulphate of copper in the like manner. He has not found in M. Becquerel's pair a dynamic activity in relation with its chemical activity, when using, in order to appreciate the

force of its current, the action upon the magnetised needle, or the magnetisation of soft iron. M. Fechner, on the other side, had made a great number of experiments, with a view of proving that the development of electricity in Becquerel's pile was due to the respective contact of the platinum plates with the acid and with the potash. He operated, by means of four successive glasses, the two extreme ones of which were simply filled in general with a conducting solution of nitrate of potash, and the two middle with two solutions, intended for acting upon each other, in particular nitric acid and potash. He also called the two extreme glasses *conductors*, and the two intermediate, *producers*. The experiments of Fechner had been directed not only upon nitric acid and potash, but also upon a great number of other liquids. He had even substituted plates of other metals for platinum plates, which complicated the results, by making the action of the liquids upon the plates intervene between the mutual action of the two liquids, producers of electricity; — an action, which we have studied in the preceding paragraph. As far as concerns more particularly Becquerel's pile, Fechner had demonstrated that, in order that the effect of this pile may be energetic, it was necessary for the platinum to be in contact with the nitric acid, and that it lost almost all its force, when the experiment was so arranged, that the plates of platinum were plunged into two vessels, filled with nitrate of potash, respectively connected, by means of moist conductors, with the nitric acid and the potash, which still act chemically upon each other. Latterly Matteucci has taken up this subject, and while still confirming the fact, pointed out by Fechner, he arrived at some very interesting results upon the electric effects, that arise from the mutual action of various solutions upon each other.

After certain experiments upon the intensity of the current, obtained by the action of different acids upon potash, and upon certain oxides, and having recognised that the employment of nitric acid is always preferable, he has demonstrated, as Fechner had done, the considerable influence that is

exercised over the intensity of the current by the fact, that the nitric acid is in contact with the platinum, and he has succeeded in finding voltaic combinations of two liquids capable of producing still more powerful effects than Becquerel's pile. The following is the arrangement, that he has adopted for making these various experiments: — one of the liquids is contained in a glass bottle, into which is plunged a cylindrical vessel of porous earth, which is filled with the other liquid; two platinum plates about an inch wide, and four inches high, connected together by a metal clip, plunged into the two liquids. M. Matteucci has also, in certain cases, placed both the liquids in two porous cylinders, both plunged into sulphuric acid, diluted with eight or ten times its volume of water. It was thus that he satisfied himself that the current was almost as powerful, even when the potash and nitric acid were not immediately in contact, but were both in contact with the sulphuric acid, provided that the nitric acid was always well in contact with the platinum. The electric current was measured by the deviation of the needle of the comparable galvanometer of Nobili, and by the quantity of acidulated water, decomposed in a voltameter, the platinum wires of which were $\frac{1}{20}$ in. in diameter and 1 in. in length. In some the current was measured by the weight of copper deposited upon the negative electrode, which was in this case a platinum plate, similar to that employed in the pile.

M. Matteucci's experiments had essentially for their object the study, not only of simple pairs, but of piles, formed of pairs of two liquids, as M. Becquerel's oxygen pair. The liquids, successively tried, were, on the one hand, as attacked bodies, concentrated solutions of caustic potash, protosulphate of iron, sulphate of potash, hyposulphite of soda, pentasulphuret of potassium, monosulphuret of potassium*; on the other hand, as attacking bodies, pure and concentrated nitric acid, a concentrated solution of chromic acid, a solution

* The monosulphuret is obtained by saturating with sulph-hydric acid, one part of potash, and mixing it with one part, remaining in a state of caustic potash. With regard to the pentasulphuret, it is prepared by boiling a concentrated solution of caustic potash with an excess of sulphur.

of sulphuric acid, diluted with nine times its volume of water.

M. Matteucci first satisfied himself that a single pair of pentasulphuret of potassium and nitric acid decomposed water in the voltameter and produced a constant deviation of 70° or 76° in the galvanometer. A very distinct spark may likewise be obtained with this pair, by interrupting the circuit through mercury. The monosulphuret of potassium, placed in lieu of the pentasulphuret, gives the same effects, with the simple difference that the action is more constant. The two sulphurets of potassium also form with sulphuric acid, pairs less powerful it is true, than with nitric acid; but then we see the hydrogen liberated around the plate, that is plunged into the acid. We may increase the force of these pairs by covering the platinum plate, that is plunged into the acidulated water, with a coating of peroxide of lead; but then we cease to see the hydrogen liberated. A pair formed with a concentrated solution of hyposulphate of soda and nitric acid, or chromic acid, decomposes water, and gives a constant deviation of 40° to 45°. By substituting for the acids water rendered conducteous by means of a little sea-salt, the electric effects that are obtained, are scarcely sensible with the different solutions, indicated above.

M. Matteucci was not content with studying the effect of a single pair; he formed with these pairs piles, the power of which he measured. These various piles, composed of twelve pairs, were at first two piles, one nitric acid and potash, the other nitric acid and pentasulphuret of potassium. This latter is the most powerful of all those which can be formed with two liquids. Indeed, it gave a fixed deviation of 75°, and $4\frac{1}{3}$ cub. in. of mixed gases; whilst that with nitric acid and potash, gave only ·67 cub. in. in five minutes, and a deviation of only 46° to 48°. A Grove's pile, also of twelve pairs, liberated in the same voltameter, 8 cub. in. of the gaseous mixture; that is to say, not quite the double of that which was given by the nitric acid and pentasulphuret pile. On interposing between the nitric acid and pentasulphuret, contained in two porous cylinders, a layer of diluted sulphuric acid,

the effects of this pile are in no way changed. A pile of twelve pairs, each of which was formed of a saturated solution of sulphurous acid and nitric acid, contained in porous cylinders, plunged at the same time in the sulphuric acid solution, gave from 40° to 45° of deviation, and ·36 cub. in. of the mixed gases in five minutes. The effects were very nearly the same on substituting, for the sulphurous acid solution, that of sulphate of potash. Finally, with twelve pairs, formed of nitric acid and a concentrated solution of the sulphate of protoxide of iron, a fixed deviation is obtained of 16°, and 4·88 cub. in. of the gaseous mixture in five minutes.

M. Matteucci succeeded in proving that the liberation of electricity, which takes place in piles of two liquids, is independent of the metallic arc; and this, by employing, for connecting these liquids, the nervous filament of the galvanoscopic frog, by means of two glass tubes, filled with sand, rammed down and moistened with a solution of sea-salt or pure water, communicating on the one hand with two different points of the nervous filament, and on the other with the two liquids of the pairs.

The inspection of the liquids, after the circuits of the different piles has been closed for a certain time, shows, moreover, in an evident manner, the presence of an oxidising chemical action, or a liberation of oxygen around the positive platinum plate; and a deoxidising action, or liberation of hydrogen around the negative.*

Finally, in order to demonstrate well the chemical origin of the electricity developed in the piles of two liquids, M. Matteucci endeavoured to measure at the same time the electrochemical effects, produced in the pairs of a pile in action, and that which takes place in the voltameter, wherewith the circuit is closed. With the pile of twelve pairs, nitric acid and potash, he always found the quantity of oxygen a little less in the interior of the pile than in the voltameter, especially when the action was slow, and the surface of the plate, in contact with

* We must not forget that we call that plate *positive*, whence the current sets out, in order to go into the liquid; and thence to the other plate, which we term *negative*, although it is the one, whence the current seems to go, in order to traverse the circuit.

the potash, was considerable. It is possible that this difference is due either to the formation of a bioxide of potassium, or to an action of the oxygen upon the platinum, in presence of the potash. Perhaps, in these actions might be found the cause of the evident influence that the contact of the platinum with the potash exercises over the intensity of the current, produced by this pile. With a pile of twelve pairs of diluted sulphuric acid, and monosulphuret of potassium, the quantity of hydrogen, collected in the acid, was exactly the same as that furnished by the voltameter. With a pile of twelve pairs of monosulphuret of potassium and sulphate of copper, the law of equivalents is found equally verified. Thus the quantity of copper, deposited upon two platinum plates, taken, one in one of the pairs, the other in a voltameter, filled with a solution of sulphate of copper, is found to be almost exactly the same. In one experiment it was 14·68 grains, on the negative plate of one of the pairs, and 14·64 grains on the negative electrode of the voltameter.

It is more difficult to collect and to measure the oxygen, liberated in the interior of the pile; however, M. Matteucci has succeeded in this, by forming a pile with pairs, composed of a solution of sulphurous acid, and a solution of nitrate of silver, containing ten parts of water by weight for one of nitrate. After having, by a comparative experiment, estimated the quantity of sulphuric acid, that is formed by the oxygen of the air, he was able, by dosing it by means of baryta, to determine exactly the proportion of this acid, that is produced in the sulphurous acid, by the oxygen itself, that arises from the action of the pile. After several essays, and by taking various precautions, he arrived at results that were very satisfactory for their accuracy. Thus having obtained 7·27 grains of silver, deposited upon the negative plate, he found, on taking account of the sulphuric acid, formed by the oxygen of the air, that the quantity of this acid, corresponding to the silver reduced, was 2·73 grains, instead of being 2·69 grains, which would be exactly the equivalent of the silver obtained. The difference between these two numbers is so small, that we may well regard it as demon-

strated that the quantity of oxygen which, arising from the decomposition of the water in the pairs, combines with the sulphurous acid, is equivalent to the quantity of silver that is decomposed in the pile. We may also remark that, in the pairs, into which nitric acid enters, such as that with nitric acid and potash, it is not only the action of the nitric acid upon the potash, which determines the current, but especially the presence of nitric acid around the platinum plate; since, provided this presence is maintained, almost as much effect is obtained by interposing a solution of sulphuric acid between the nitric acid and the potash; and that, on the contrary, the intensity of the current becomes very feeble on placing the sulphuric acid in contact with the platinum, and the nitric acid between it and the potash. These results are easy of comprehension in the theory, that we have given of the production of electricity in a voltaic pair. The action of nitric acid, like that of sulphuric acid upon potash, produces a current, in which the acid acquires positive and the alkali, negative electricity. These two electricities are immediately united upon the surface itself of contact of the two liquids, in proportion as they are separated; but if the circuit is closed, by means of a metallic arc, these two electricities are able to neutralise each other by traversing the circuit; however, they cannot do this, except by decomposing the water of the solutions, and in particular that of the potash. Now, this decomposition is excessively facilitated by the presence at the negative electrode of a body, that easily abandons its oxygen, such as nitric acid; and which thus plays, in this case, the same part, that we have seen played by the peroxide of lead in a zinc and platinum pair. The acid, like the peroxide, on being deoxidised by means of the hydrogen of the decomposed water, adds further to the force of the current. It is easy to understand that the sulphuric acid, around the platinum plate, cannot produce the same effect.

We have hitherto spoken only of the electrical effects, that accompany the mutual chemical actions of two solutions; but this is not the only action, that a solution may suffer. Thus, it may be decomposed, without the intervention of a

second solution being necessary. This is what happens, for example, when water, which holds a foreign body in solution, is made to evaporate in a heated crucible. M. Pouillet, who was the first to make this species of observation, employed a capsule, and even with more advantage a thick plate of platinum slightly hollowed, which he caused to communicate, after having heated it to redness, with the lower plate of a condenser, by means of a rod, soldered to this plate. After having satisfied himself that the evaporation of pure water did not liberate electricity, he poured successively, into the crucible, some drops of a solution, acid, basic, or saline. He observed that, with a solution of strontian, the capsule, at the moment of the evaporation, preserved the positive electricity, whilst the vapour carried off the negative; it was the same with other alkaline solutions. Ammonia alone presents a converse effect, because, being more volatile than water, it carries off the positive electricity, and leaves to the water, and consequently to the capsule, the negative electricity. With acid solutions, on the other hand, it is the water that is positive and the acid acquires negative electricity. With a solution of sea-salt it is the same. It therefore appears, from these various researches, that the electric effects, in chemical decompositions, are the reverse of those that take place in combinations. It is, moreover, what we had already remarked, in making a pair with a plate of platinum and peroxide of manganese, or peroxide of lead, plunged into acidulated water. The decomposition of the peroxide produces a current, which goes in the converse direction to that which would result from the oxidation of the metal. We may further prove the accuracy of this principle by projecting solid bicarbonate of soda, into the platinum capsule, heated to redness. This salt is decomposed, by allowing the carbonic acid to escape, which carries off the negative electricity, whilst the capsule acquires a powerful excess of positive electricity.

M. Peltier, who has studied this subject carefully, remarks that electricity is not produced in the experiments, that we have been relating, in all the phases of the evaporation, but

only at the moment when the liquid, quitting the spheroidal state, suffers a species of crepitation. He concludes from this that electricity is liberated only at the moment, in which a chemical decomposition takes place, arising from the segregation of the combined water, and not during the separation of the superabundant water.

M. Gaugain is rather disposed to see in these various phenomena the result of the friction against the sides of the crucible, of the particles of water, projected at the moment of decrepitation. His opinion is based upon the fact that slow evaporation, which is moreover accompanied also by a chemical decomposition, does not produce any effect, and, moreover, upon the fact, that the electricity developed in this kind of action does not communicate instantaneously to the condenser the maximum of charge, that it carries off, which would be the case, if an electric source, having its principle in chemical action, were the matter in question; on the contrary, the quantity of electricity increases up to a certain limit with the duration of the action; and has an invariable value, independent of the extent of the surfaces of the condenser, as is the case for friction; whilst, when chemical action is in question, not only is the charge instantaneous, as we have just said, but it increases indefinitely with the surface of the condenser employed. It was by operating upon a solution of sea-salt, that M. Gaugain made these observations. It would not appear that the electricity produced, can be due to the friction of the particles of salt against the surface of the platinum; for direct experiment made by blowing dry sea-salt in powder against the sides of a platinum crucible, heated to redness, has shown that this crucible was charged with positive and not with negative electricity. It would then be only to the friction of the water, that the effect must be due. But then, why should not distilled water produce it equally? and why should it take place as well in a wide-mouthed capsule, as in a narrow one, whilst there is electricity, liberated by the friction of pure water, in the latter case only, and not in the former?

We are therefore disposed to believe that, an electric

effect is indeed produced in chemical segregations, in like manner as there is one in combinations, and that, if its manifestation does not in general take place, except when the evaporation is very rapid, this is due, as we have already had occasion to remark in the preceding paragraph, to the fact that in this way we better avoid the immediate recomposition of the two electricities.

It is also to the decompositions of solutions, that we must in very great part attribute the electric effects, that are obtained by plunging into a liquid two platinum wires, connected to the two ends of a galvanometer, and of which one has been heated to redness, whilst the other has remained cold. Every time that the heated wire takes from the liquid positive electricity, or, which comes to the same thing, plays in the pair the part of negative metal, the electricity arises from the decomposition of the solution, and the wire plays the same part, that was played by the platinum capsule in the preceding experiments; whilst, when it acquires negative electricity, or conducts itself as the positive metal, it is probable that the electricity arises from a chemical action, exercised upon it by the solution. This is in fact the conclusion, that may be drawn from the experiments, made upon this by M. Henrici. Thus, he has found that whether with hydrochloric acid, or with a solution of potash, the heated wire does acquire negative electricity; a proof that it is attacked, which should actually have taken place in this case. With sulphuric and nitric acids, either concentrated or diluted, the heated platinum wire acquires on the contrary positive electricity, because these are solutions, that are decomposed under the influence of the heat of the platinum.

To sum up, the electrical effects, that accompany the chemical actions in which the bodies submitted to these actions are liquids, enter in a general manner into the laws, which regulate the chemical actions, in which one of the bodies is a solid and the other a liquid. However, in order to collect the electricity produced in these actions, we must necessarily employ a solid body as a conductor; it follows that, whatever precaution may be taken in order that this body may be in-

active, by choosing it among the unattackable metals, such as platinum, it is not always possible to avoid its active intervention, which, in these cases, render the phenomena more complex. This is what in particular necessarily follows from the circumstance that unattackable metallic plates, as well as those which are attackable, acquire a secondary polarity, by the mere fact that they have transmitted the currents developed in liquids. We are about to see, in the following paragraph, which is devoted to the study of this polarity, how we may take account of it.

Production of Electricity in the Chemical Action of Liquids upon the thin Films with which solid Surfaces are covered. Secondary Polarities; Gas Pile; passive Iron.

Ritter had observed that, on forming a pile of discs of the same metal, alternately with moist card, this apparatus, inactive of itself, becomes capable of giving similar effects to those of the ordinary pile, when it has been interposed for a few moments in a voltaic circuit. The action of this pile, which Ritter had called *secondary*, was the more powerful, as the current, which had charged it, was more energetic, and as the surface of the metallic discs, employed in its construction, was more considerable, and as the liquid with which the papers were moistened was a better conductor. But this action was not permanent; it ceased when the pile had acted for a few moments. Volta, having examined Ritter's secondary piles, declared that the ordinary pile did not transmit to them any charge, but that their effect was due to this circumstance, that the electric current, in traversing them, decomposed the liquid, interposed between the discs of homogeneous metal, and covered the surface of each of these discs, with two different solutions, one acid, the other alkaline, when the liquid employed was a saline solution, most frequently the case. This opinion of Volta has been completely confirmed by ulterior researches, and especially by the detailed analysis, that Marianini has made of Ritter's secondary piles. The learned Italian philosopher has demonstrated that it is not as Ritter

had conceived, to the difficulty which they oppose to the passage of electricity, that secondary piles owe their electromotive power, since the more easily they transmit the current of the active pile, the more powerfully and easily they are charged. He has equally proved that the cause of the electricity, that is liberated in secondary piles, is entirely in the alterations that are suffered by the surfaces of the metallic parts, in the portions, in which they are in contact with the moist conductors, since we may turn round and even change these latter, without destroying or even diminishing the power of these piles. Only this alteration is not due, as Marianini seems to think, to a physical modification, that the metallic surfaces might have suffered, but to a simple formation of deposits arising from the decomposing action, exercised by the transmitted current, upon the liquid of the secondary pile: deposits which, by the chemical action, that is exercised upon them by the liquid, are the origin of the electricity liberated.

We may further add (in order not to be called upon to return to this point, which is however of little importance, except, as we shall see, as far as it concerns the influence, that it exercises upon the force of the voltaic pile), that the best arrangement to be given to secondary piles consists in uniting a series of vessels, filled with a conducting solution, saline for example, by homogeneous arcs, of copper, and even of gold or platinum (*fig.* 314.); then, when a current, which should

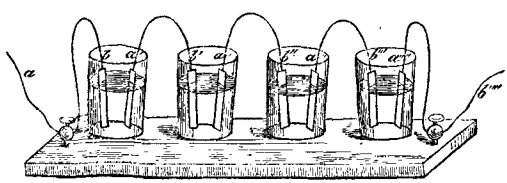


Fig. 314.

have more intensity, in proportion as the number of inactive pairs is more considerable, is transmitted through the system of inactive pairs, the secondary pile is found to have acquired an electric charge. It gives signs of tension at its two extremities, and a current, capable of acting upon the

needle, of producing heat, and even a spark, and of decomposing water. Only the nature of the electricity, accumulated at its two poles, as well as the direction of the current that is established when these poles are united, indicates that these extremities have acquired contrary electricities to those of the poles of the voltaic pile, with which they have been placed in communication. This is an evident consequence of the nature of the deposits, which the initial current has determined upon each part of the metallic arc, and of the direction of the current, to which the chemical action of the liquid upon these respective deposits gives rise.

In order well to analyse this order of phenomena, we must begin by studying it upon a single secondary pair, and not upon an entire pile. With this view two plates of the same metal are plunged into a vessel, filled with a conducting liquid; it is preferable to employ platinum, in order to avoid the direct chemical reaction of the liquid upon the metal itself. The current of a voltaic pile is made to pass for some time through the liquid, employing as electrodes plates of metal; then, after having interrupted the current, the plates are put into communication with a galvanometer, and a powerful current is immediately observed, which lasts for some instants, and the direction of which is the reverse of that which had been transmitted. This current is termed *secondary*, in opposition to that which had charged the apparatus, and which is termed *primary*; and we designate, as we have already seen, under the name of *secondary polarity*, the property, which the metal plates have acquired, in transmitting the primary current.

Whenever the electrolytic liquid is a saline solution, the current produced by the secondary polarities is easy of explanation, as M. Becquerel had first clearly demonstrated; in fact, there is deposited upon the surface of the negative electrode, a film of alkali, and upon that of the positive electrode a film of acid, which, by the action, that is exercised upon them by the solution, ought to produce a current directed from the alkali to the acid in the liquid; and, consequently, from the plate, that had served as a positive electrode, to

that which had served as negative electrode, in the wire of the galvanometer, by which they are united. We can produce the same current without employing the electrolytic solution; but by simply plunging one of the plates into an acid, and the other into an alkali, and then placing them in a conducting solution, after having united them with the two ends of a galvanometric wire.

It was less easy to explain the cause of the secondary current developed when the electrodes which have acquired polarity are simply plunged into pure or acidulated water; and when, consequently, the deposit, with which they are covered, can be only oxygen or hydrogen. I had already, in 1826, proved the existence of secondary polarities upon platinum plates or wires, when the solution is only water, slightly acidulated with sulphuric acid. I had attributed them to a particular state of polarity, which the electrodes themselves might have contracted under the influence of the current; but M. Becquerel having demonstrated that, when the circuit is all metallic, the phenomenon no longer takes place, and the electrodes present it merely in the parts of their surface, that have been in contact with the electrolytic liquids, it would become natural to see its cause, in the deposit of small gaseous films upon the part of the electrodes, where the liberation of the gases, that arise from decomposition, has been brought about. It was M. Matteucci, who first confirmed this explanation by direct experiments made with very pure water. He assured himself that the polarities remain upon the platinum plates for a very long time, that they may be destroyed by heating these plates to redness, and that a single plate was sufficient for exciting the current, when employed with another, which has not been used as an electrode; but yet, in this case, the plate upon which the hydrogen is deposited, gives a more decided effect than that, upon which the deposit has been oxygen.

In order to show that there is actually a film of hydrogen, adhering to a plate which has been used as a negative electrode, and one of oxygen to a plate, which has been used as a positive electrode, M. Matteucci introduced the former

into a small graduated receiver filled with oxygen, and the latter into a similar receiver filled with hydrogen. In each of the receivers, there was a diminution of volume, which can only arise from the combination of the oxygen and hydrogen contained in the two receivers, respectively with the hydrogen and oxygen remaining adhering to the plates. In one experiment the diminution was ·024 cub. in. in the oxygen and ·012 cub. in. in the hydrogen. We may call to mind that I obtained a similar result on reversing the direction of the current in the electrolytic decomposition of acidulated water; and by showing that the quantities of gas liberated are less than they ought to be, when we take as a negative electrode the plate, that has served as positive electrode and reciprocally.* Moreover, M. Matteucci has equally succeeded in this case as he had done in the case of alkaline and acid deposits, in demonstrating, by a direct experiment, that the current is indeed due to films of hydrogen and oxygen, that are determined by the electrolytic decomposition of the water. With this view, he placed platinum plates in very pure hydrogen and oxygen; then, after having drawn them out and united them to the wire of a galvanometer, he plunged them into distilled water, and obtained deviations, that amounted to as much as 90°. The current always goes in the liquid from the plate, which has been in the hydrogen, to that which has been in the oxygen. The films of gas obtained in this manner are as adherent as those, which are determined by electrolytic decomposition; it is only necessary to leave the plates in the gases for about ten minutes, in order to obtain the maximum effect. A current can also be obtained by employing only one plate, which has been plunged in hydrogen or in oxygen, and uniting it with another, which has not been placed in contact with any gas. In these experiments, it is necessary to employ plates of platinum or of gold, and to be assured, before imparting to them the secondary polarity, that they do not of themselves produce any current.

M. Schœnbein, in the numerous researches, that he has

* *Vide* above, Vol. II. p. 414.

made upon this subject has remarked that, if we separate into two compartments by a porous partition, the vessel in which distilled water is electrolytically decomposed, a very decided current is obtained by plunging into the water of each of these compartments a plate of platinum, that has not been used as an electrode; and he satisfied himself that this property appertains to the water of the compartment, in which the hydrogen is liberated; for, it subsists, when this water is transported into another vessel, or is in contact by the intervention of another membrane with water chemically pure. The water, in which the oxygen had been liberated, does not possess the same property. This arises therefore evidently from the hydrogen dissolved in the water; and, in fact, for developing it, we have merely to cause hydrogen to dissolve artificially in pure water without having need to employ for this purpose electrolytic decomposition. It is indispensable, in order to succeed, that the metallic plate, which plunges in the hydrogenated water, be of platinum; that which plunges in water, whether oxygenated or pure, may be indifferently platinum, gold or even silver. The current always travels directly from the water, in which the hydrogen is dissolved, to the water that is in contact with the former by the intervention of the porous partition. M. Schœnbein has also observed that water, in which oxygen has been made to dissolve, either directly or by transmitting into it a current, the positive electrode of which is in contact with it, is completely inactive with ordinary water, even in the case, in which the circuit is closed by plates of platinum, that plunge into the two liquids; yet platinum and gold, that have been employed as positive electrodes in water, acquire thus a very decided secondary polarity, — a polarity, that is not imparted to them by their simple contact with oxygen, contrary to what had been observed by M. Matteucci. M. Schœnbein thinks with justice that this negative polarity is communicated to the platinum and the gold by a film of ozone or ozonised oxygen, which is deposited upon their surface; for, he is able to impart the same property to these metals by simply plunging them for

several moments in air, ozonised by means of phosphorus. Water that is agitated in a large flask, filled with ozonised air, with pure water and plates of platinum, that have not been polarised, gives a current, that goes from the pure water to the ozonised water. The phenomenon takes place as in the case, in which the water holds in solution chlorine, bromine or iodine; substances, which, like ozone, impart to platinum and gold, when they form a deposit on their surface, negative polarity. In general, as M. Schœnbein was the first to observe, platinum plunged into water, which holds in solution chlorine, bromine, iodine or even ozone, comports itself opposite platinum which is plunged into pure water, separated from the former by a simple porous partition as a peroxide (peroxide of lead), which might form a pair with a plate of platinum in ordinary or slightly acidulated water. It would seem at first sight that platinum plunged into the solutions, that we have been naming, ought on the contrary to have comported itself as a positive metal, on account of the chemical action, that it must suffer on their part. But the phenomenon is altogether different; under the influence of platinum, chlorine, bromine, iodine decompose water as a peroxide does; and it is easy to see that the electrolytic chain is then established, so that the current travels in the liquid from the platinum plate, that is plunged in the pure water, to that which is plunged in the solution, all the hydrogens of the molecules of water being turned on the side of the latter, and the oxygens on the side of the other. Ozonised oxygen, comports itself like chlorine, bromine and iodine; whilst it is not the same with ordinary oxygen, which is due to the circumstance that the former decomposes water under the influence of platinum, and not the latter. In this general property is found the explanation of the fact, observed by several philosophers, that the solution of chlorine, bromine, and even iodine facilitates the production of electricity in a pair, that is plunged in these solutions, as well as the decomposition of water, in which these substances are dissolved. Indeed, it is a chemical force, which is added to that of the negative metal of the pair, or of the negative electricity of the pile, in order to separate the hydrogen from its oxygen, in each of

the molecules of the filament of water, which is already polarised by the positive metal of the pair, or by the positive electricity of the pile.

Mr. Grove has analysed with great care the phenomena, that are engaging our attention, and has drawn from them the most remarkable consequences. He was the first to show that the action of hydrogen and oxygen upon water, under the influence of platinum, is able to give rise to a constant current, and not only to currents of a more or less short duration. With this view, he took two tubes, closed at their upper part, and each containing a platinum plate, able to communicate exteriorly by means of pieces g and g' attached (*fig.* 315.). He filled these tubes with acidulated water; he then introduced hydrogen into one, and oxygen into the other, taking care that the platinum plate was plunged, half in the gas, and half in the liquid; the two tubes being then placed in communication, by means of a solution of sulphuric acid, in which they plunged by their lower part. A constant and decided current was obtained by connecting the two platinum plates by the wire of a galvanometer. It is necessary for these plates to have been previously well cleaned. The tubes may be filled with the desired gases by causing a voltaic current of sufficient force to pass through the liquid, to which the plates serve as electrodes. If the precaution is taken of allowing the metallic communication between the plates of platinum to subsist for a long time successively, by which the current is maintained, we gradually perceive the oxygen and hydrogen diminish in the two tubes, in the proportion of one volume of oxygen for two of hydrogen.

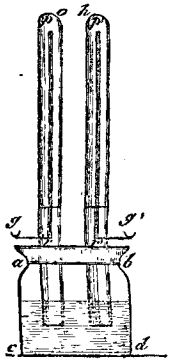


Fig. 315.

Mr. Grove having recognised that the action can take place only at the place where the liquid, the gas, and the metal are in contact, endeavoured to obtain as great a surface of action as possible. With this view, he employed plates of platinum platinised, that is, covered with a thin pulverulent

film of platinum, according to the process of Mr. Smee.* The first experiments were made with platinum wires instead of plates; and having connected fifty similar pairs voltaically, so that the wire plunged in the hydrogen of the one, communicated with the wire plunged in the oxygen of the other, he succeeded in obtaining a pile, the poles of which caused a gold-leaf electroscope to diverge. These same poles, when they were terminated by charcoal points, gave between them a spark visible in open day. The pile produced a shock, that might be felt by five persons connected together, could decompose iodide of potassium, hydrochloric acid, water acidulated with sulphuric acid; acted on the magnetised needle, &c. The effects were the same, whether the pile was charged with oxygen and hydrogen, arising from the electrolytic decomposition of water, as with oxygen and hydrogen, prepared by purely chemical processes. This new pile or battery, was termed by Mr. Grove the *gas pile or battery;* and he gave to it various forms; the last at which he stopped, appears to us the most convenient.

The following is the description of it:

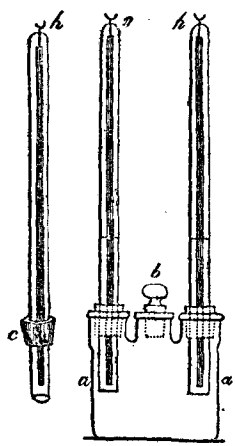


Fig. 316.

Each cell is formed (*fig.* 316.) of a glass bottle *a* with three necks, similar to the bottles of *fig.* 308. which we have used in the construction of the pile, for the purpose of establishing the law of equivalents in the interior itself of the pile. A glass stopper *b* closed the centre neck; tubes *o* and *h* are accurately adjusted in the other two openings by means of collars of glass, which form part with these tubes, and which are ground exteriorly with emery, as is the stopper of the opening; each tube contains a plate of platinised platinum, not quite so long as the tube,

* This process consists in employing the plates of platinum, that are to be platinised, as negative electrodes in a solution of chloride of platinum; they are soon covered with a deposit of pure platinum, but in the state of great division.

which is terminated above by a thick platinum wire; this wire traverses the top of the tube, into which it is hermetically sealed, and carries a small copper cup, that is filled with mercury *, which, by means of bent wires, serves to establish communication between the successive pairs, as is seen in *fig.* 317.

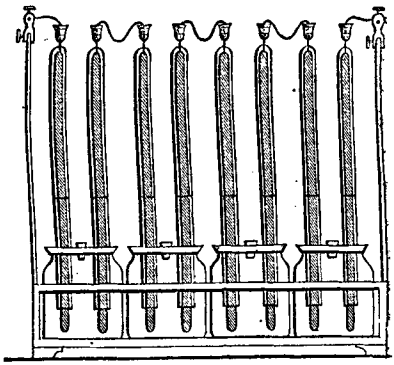


Fig. 317.

In order to introduce the acidulated water into the tubes we begin by completely filling the bottle, and then turn it over, taking care to retain with the fingers, the glass stopper and the tubes; the latter being below, are soon filled with the liquid, especially if care is taken to shake it a little in order to drive out the air. Finally, the gases are introduced into each tube, either by means of a bent tube, which communicates with the receiver where the gas is; or (which is more convenient) by bringing about, by means of an ordinary pile, the decomposition of the water in each bottle. As only one-half less oxygen is required than hydrogen, one of the tubes is narrower than the other, and care must be taken to introduce the oxygen into this latter. Moreover, the tubes are carefully graduated, so as to be able to measure the gaseous volumes. The advantage of this arrangement of the gas pile is, first, that, by plunging the bottle into the pneumatic trough, we are enabled to detach each tube, in order to measure and to examine the gas, that it contains; moreover, as the interior

* Small metal clips may be advantageously substituted for the cups.

of the bottle is perfectly impermeable to air, and finally being exclusively composed of glass and platinum, it can contain electrolytic liquids of every kind, even the most corrosive.

A single pair of the gas pile, constructed according to the description, that we have just given of it, is sufficient for decomposing iodide of potassium; only four are necessary for decomposing the acidulated water of the voltameter. With two pairs the decomposition is brought about with sufficient rapidity to produce, in one experiment, at the end of thirty-six hours, 2 cubic inches of the gaseous mixture in the voltameter; at the same time, the liquid mounted in each of the hydrogen gas tubes of the pile, 1·46 cubic inches, and in each of the oxygen, ·67 cubic inches, which makes in all 2·12 cubic inches that have disappeared in each pair; — a quantity almost exactly equivalent to that, which had been liberated in the voltameter. Frequently, a little more hydrogen disappeared in the pairs, than the quantity equivalent to that of the oxygen absorbed, which is due to the combination, that is brought about, under the influence of the platinum, between the hydrogen that is in the tube, and the oxygen dissolved in the water. This species of local action takes place equally, whether the pair forms part of the voltaic circuit, or is not in action.

In order to demonstrate the accuracy of this explanation, it is necessary to drive out as much as possible from the acid solution, all the air that is dissolved in it; and for this purpose we have merely, after having caused this solution to boil well, to place the trough and the two tubes, that contain it, for twenty-four or forty-eight hours, in vacuum. Afterwards, by means of a voltaic current, one of the tubes is filled with oxygen, and the other with hydrogen; then, after having left the apparatus for two or three weeks, without touching it, the volume of hydrogen is still found to have diminished a little, but much less than when the air has not been driven out. The volume of oxygen has not changed. On the other hand, another cell is taken, and, far from driving the air from it, as little liquid as possible is put into it, only as much as is necessary for the tubes to dip into the bed of

liquid by their lower extremities; the rest of the bottle is filled with atmospheric air, but the air does not communicate with the external air, the bottle being hermetically closed. At the end of about a fortnight, it may be proved that the hydrogen has considerably diminished; in one experiment it diminished 1·95 cubic inches; and, if we introduce into the cell at the moment when it is opened a lighted taper, it is seen to be immediately extinguished, because nothing remains but nitrogen in the upper part of the bottle, and the oxygen of this air has been absorbed gradually by the liquid, in order to come and combine with the hydrogen. Thus, hydrogen, under the influence of platinum, combines with the oxygen, dissolved in the liquid with which this hydrogen and platinum are in contact; and the liquid, taking up oxygen, in proportion as its own disappears, is thus able to remove it gradually and almost entirely from the atmospheric air, that is in contact with it.* Mr. Grove has succeeded in obtaining, by this action alone, a tolerably energetic current, by suppressing the oxygen in the gas pile, and replacing it simply by acidulated water; its effect is at first almost as powerful as that of the pile in which are the two gases equally; but the action diminishes rapidly, whilst it is constant in the other.

M. Schœnbein attributes the liberation of electricity in Grove's gas pile to the hydrogen, and consequently to the chemical action, that takes place between it and the acidulated water; he considers that the oxygen, in contact with the platinum, has no other effect than to depolarise

* Mr. Grove has endeavoured to apply this property to the eudiometric determination of the quantity of oxygen, that is contained in the air. With this view, he places in a narrow trough, in which there is some diluted sulphuric acid, two narrow tubes, six or seven inches in length, filled with atmospheric air. These tubes carry a graduation. In one of the tubes is placed a plate of platinised platinum, which is placed in metallic communication with a similar plate, placed in a tube full of hydrogen gas, which plunges into the same vessel; the other tube, full of air, serves only to determine how much is dissolved, during the continuance of the experiment. In one experiment, which had lasted two days, the liquid had mounted twenty-two divisions in the former tube, and one in the latter; which gives twenty-one per cent. for the quantity of oxygen that is found in a certain quantity of air. At the end of several days, the result had not changed.

those plates upon which the voltaic action, so long as the pile is in action, constantly brings hydrogen; which then, instead of remaining in a thin film upon the metal, is carried off by the oxygen that is found there, by combining with it. It should necessarily follow from this, that the effect of the pile is no longer weakened, as when the hydrogen remains adhering to the platinum. But, even admitting the reality of effect, pointed out by M. Schœnbein, can we not say that the chemical combination of the oxygen with the nascent hydrogen, at the same time, that it depolarises the platinum, contributes to the production of electricity, as does the peroxide of lead, which covers the platinum in the zinc and platinum pairs, as we have seen above? Moreover, the presence of the oxygen is necessary for the production of the current. Thus, Mr. Grove has satisfied himself that, in the pile, in which solution of sulphuric acid is substituted for it, there is no effect produced if (the pairs, being placed in an atmosphere of nitrogen) there can be no oxygen dissolved in the liquid. He has also shown that an active pile may be equally formed with one or other of the two gaseous elements, either by substituting for the oxygen an electrolyte, that has great affinity for hydrogen, such as nitric acid; or by substituting for the hydrogen an electrolyte that has much affinity for oxygen, such as protosulphate of iron. It is true that the nitric acid and hydrogen pile is more powerful, and especially more constant than that of oxygen and protosulphate of iron; but this is due to the nature of the chemical action, and to the circumstance, that a great part of the protosulphate passes into the state of sulphate of peroxide, by the direct effect of the oxygen of the air; which diminishes the action of the oxygen of the pile.

We may therefore regard the two gases as both of them contributing directly to the voltaic effect in the gas pile. With regard to the theory of this pile, it is exactly the same as that, which we have laid down for piles, in which metals are the active elements. The hydrogen, adhering to the surface of the platinum in the line of contact between the surface and the liquid, polarises the filaments of

this liquid, so that the negative oxygens of all that their particles are turned on its side, and the positive hydrogens on the other; the oxygen, adhering to the surface of the second platinum, produces upon the same filaments an analogous effect, which is added to the former, since it acts in the same direction. When the two platinum plates are united metallically, the free negative electricity of the plate, which is in contact with the hydrogen, unites with the positive of that, which is in contact with the oxygen, the decomposition and recomposition of the successive molecules of the filaments is brought about; and at the same time that the oxygen of one of the extreme molecules combines with the hydrogen, adhering to the platinum, the hydrogen of the other extreme molecule combines with the oxygen, adhering to the other platinum. We may add, in support of the theory, that we have been laying down, that Mr. Grove has demonstrated by direct experiments that the active part in the gas pile are the portions of platinum which in each tube are at the level of the liquid in proportion as it rises in the tube; and these are in fact the only parts where contact can at the same time take place between the liquid and the gas, adhering to the platinum.*

This affinity at a distance, as Faraday has so well characterised it, which is exercised by the intervention of the liquid molecules interposed on the one side, and of the metal arc, which connects them on the other side, between the hydrogen and oxygen, that are separated by the liquid, may take place at distances infinitely small, and constitute, as in ordinary voltaic pairs, local action. This happens when the

* However, it follows from an observation of M. Jacobi's, confirmed by M. Poggendorff, that the combination of oxygen and hydrogen, under the influence of platinum, may take place, even when these gases are not immediately in contact with the liquid, and are separated from it by the electrolytic liquid. Thus M. Poggendorff, having liberated 3·4 cub. in. mixed gas in a voltameter of plates newly platinised, having taken care that the plates should always remain below the level of the liquid, he observed that the re-absorption of the gases took place with immense rapidity; such, that in a few moments several tenths of a cubic inch had disappeared; the re-absorption is then relaxed, but, it ends by being completely accomplished. It follows from this fact, that combination does not take place exclusively at the spot, that Mr. Grove has assigned to it; a circumstance, however, of no great importance.

liquid in contact with the hydrogen contains dissolved oxygen. The molecules of water, polarised by the hydrogen that adheres to the platinum, in the portion wherein the platinum is at the level of the surface of the liquid, find oxygen upon the platinum beneath this surface. There is immediately a small molecular circuit formed. It is not therefore the dissolved oxygen, that combines directly with the free hydrogen, but this oxygen serves to form an active circuit, analogous to that, which takes place in the ordinary pair, with the simple difference that it is molecular and that the metallic arc, that enters into its formation, is only a small portion of the surface of the platinum, placed in the hydrogen tube; it is, in like manner, the oxygen, adhering to the platinum plate, placed in the solution of sulphuric acid, which serves for the production of the current, when this solution is substituted for the oxygen in the tubes. This oxygen is useless when, instead of a solution of sulphuric acid, we take nitric acid, which parts so easily with its oxygen, that its employment is preferable for the force of the pile to that of oxygen itself. Indeed, three pairs are, in this case, sufficient for decomposing water, whilst it requires four with the oxygen-gas pile. The peroxide of lead produces a still greater effect; a single pair, hydrogen and platinum, covered with peroxide of lead, easily decomposes water. We may add that, in the gas pile, the oxygen, instead of being simply adherent, is very probably combined with the platinum, so as to form an oxide easily reducible. This results, from an examination of all the circumstances, that facilitate the action of the apparatus, such in particular as the pulverulent state of the platinum, and which is in other respects in accordance with the facts, that we have already related in favour of the oxidation of platinum.*

Grove's gas pile presents to us a striking example, and I may say a pointed one, of Faraday's law of equivalents. We see the combination of one equivalent of hydrogen and one equivalent of oxygen produce a current, capable of decompos-

* Vol. II. p. 416.

ing one equivalent of water; that is to say, a quantity of water precisely equal to that, the formation of which has given rise to this current. At first sight, we do not conceive that the force, which produces the formation of water, would be sufficient to surmount the force, by which its constituent molecules are already united. It is easy to reply to this objection as far as concerns the decomposition of water in the voltameter; for a decomposition cannot take place, except so long as there is more than one pair, four at least, and until consequently we have quadrupled, conformably to the theory of the pile, the decomposing force. If the question is in reference to a single pair, the platinum plates of which are united metallically, the objection is more specious, and it has been proposed by Mr. Grove itself. However, we must remark, that each molecule of the filaments of water, interposed between the two plates of the pair, is subjected to two decomposing forces, which act in the same direction; the one, which draws oxygen from the side of the platinum plate, where the hydrogen is; the other, which draws hydrogen from the side of the platinum plate, where the oxygen is. What one of these actions cannot do, when it is alone, as is proved by experiment *, the two united bring about; for if we take one of the molecules of water in the filament, it is easy to see that the affinity of its hydrogen for its oxygen is combated at once by the force with which its hydrogen is attracted by the oxygen of the following molecule, and by that with which its oxygen is attracted by the hydrogen of the preceding molecule, and so on for all the others.

Mr. Grove has made a very great number of experiments upon the gas pile by substituting other gaseous substances for the oxygen and hydrogen, either separately or simultaneously. The experiments have all given results perfectly conformable to the theory, that we have laid down. Thus, nitrogen put in place either of the oxygen or the hydrogen, produced no effect. The peroxide of nitrogen, associated with oxygen, in like

* Indeed, no current is ever obtained, and, consequently, no decomposition of the electrolyte with a single pair, when the hydrogen is suppressed, the oxygen alone being left, or when, leaving only the hydrogen, care is taken to drive out all the oxygen, that might be found dissolved in the liquid.

manner, produced no sensible effect; it was not the same with the deutoxide, which gives a slight current with oxygen; and diminishes when the circuit has been a long time closed, in the proportion of four volumes of deutoxide for one of oxygen. Associated with hydrogen, the two gases produce a decided current; the volume of deutoxide diminishes one half, and the gaseous residue is nitrogen; the volume then increases gradually by the addition of hydrogen. The protoxide does not undergo any change of volume, but its chemical change is detected by the absorption of the hydrogen, that forms the pair with it. Olefiant gas seems to give a continuous, but very feeble current, with oxygen. The gases that appear to be the most efficacious, are, on the one hand, oxygen and chlorine; and on the other hydrogen and oxide of carbon. Chlorine and hydrogen form so powerful a combination, that two pairs are sufficient to decompose water in the voltameter; chlorine and oxide of carbon likewise produce considerable effects, although less energetic than chlorine and hydrogen. But, the extreme solubility of chlorine renders its employment by no means satisfactory for the production of a current of some duration. Oxygen and oxide of carbon are of the four combinations that may be made with the four gases, indicated above, that which has the least energy; however, a pile of ten pairs thus charged, decomposes iodide of potassium, and a little water of the voltameter.

Mr. Grove, having proved that nitrogen was inactive, endeavoured to employ it as a solvent of some bodies, such as phosphorus and sulphur. With this view, after having filled with nitrogen, one of the tubes of the pair, and the other with oxygen, he introduced phosphorus or sulphur into the nitrogen by means of a rod terminated by a small cup, in which he lodged the substance. The pair thus formed (*fig.* 318.) gave a powerful current; only when the body introduced was sulphur, it was necessary to raise the temperature, which was done by means of a simple iron ring, furnished with a handle, which was passed over the tube containing the sulphur and the nitrogen, after having sufficiently heated it to bring the sulphur to the liquid state. In these ex-

periments, it is the vapours of phosphorus and those of sulphur, which, lodged in the inactive nitrogen, play the part, that the hydrogen played in the gas pile, and combine at a distance, under the influence of the platinum, as this gas did, by the intervention of the electrolytic liquid, with the oxygen, contained in the other tube. Piles of ten pairs, charged with oxygen and the vapour of phosphorus, decompose water; and it is found, on weighing the phosphorus, before and after the experiment, which is made to endure longer in proportion as the exterior temperature is lower; and by measuring, in like manner, the volume of oxygen, that this gas and the phosphorus have diminished almost in an equal proportion to that of their equivalent, and the equivalent of water, decomposed by the current.

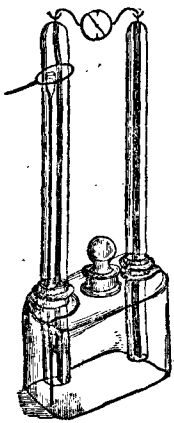


Fig. 318.

It is, therefore, now well established, by Mr. Grove's researches, that the action of elastic fluids in their contact with an electrolytic liquid may, under the influence of platinum, develope an electric current; and that this electro-chemical action is subject to the same laws as the others, and in particular to the law of equivalents. With regard to the force of this action, it depends not only upon the nature of the gas and of the electrolytic liquid, but also on that of the metals, whose presence determines the chemical action. The same metal varies in this respect with the nature of its surface. Thus, M. Poggendorff has remarked that well-polished plates of platinum may acquire a maximum of polarisation, superior to that of platinised plates; but that the maximum is more rapidly attained with these latter, and that it varies less by the change of the force of the current, that produces the polarisation, than that of polished plates. Indeed, the current produced by the films of gas, with which the surfaces of the electrodes are covered, that have been employed for decomposition, and which have thus acquired secondary polarities, varies with the force of the current, that has pro-

duced these polarities. We shall see this in the paragraph, that we shall devote to the measure of electromotive forces, in explaining how we have succeeded in determining that of the gases in the different circumstances under which they are found, in the same manner as that of solids has been determined; we shall equally see the importance that is presented by this determination in the appreciation of the electro-motive force of piles, and in that of the influence that is exercised over the force by the interposition in piles of inactive pairs; for, the secondary polarities, that are acquired by metals, which have formed part of a current, are almost always due to gaseous films deposited on their surface by the current, and consequently, their influence, which tends to produce a contrary effect to that of the current, which has given rise to them, cannot be exactly estimated, so long as we are unacquainted with the electro-motive force of gases.*

However, we may at this time explain the influence of certain causes upon the diminution of the resistance, that is presented to the transmission of the current, by the electrodes, that serve for the decomposition of acidulated water in the voltameters. Thus, when water is decomposed with a single nitric acid pair, and even with a peroxide of lead pair, the action is very quickly arrested or extremely enfeebled by the effect of the polarisation of the electrodes, which exercise an electro-motive force, opposed to that of the pairs. Now, in order to give to it all its primitive vivacity, we have merely to change the direction of the current in the voltameter; because then we cause the two electro-motive forces to act in the same direction. But soon the new polarisation, that the electrodes acquire, weakens the current anew; so that, in order to restore to it afresh its power, it is necessary again

* It may happen that, in certain gases, the power of a film of gas upon the surface of a metal, instead of diminishing, increases the electro-motive force of this metal; thus, as M. Buff has observed, when we have caused a thin film of hydrogen to deposit upon the surface of zinc, by employing it as a negative electrode in the decomposition of water, this plate becomes powerfully positive in respect to another similar one, that has not been placed under the same conditions; which is proved either by the charge, which they give to the condenser, or by the direction of the current, which they produce, when forming a pair.

to change its direction. By bringing about therefore these alternations in the direction of the current, we easily obtain a tolerably powerful decomposition of water in the voltameter, by means of a single pair. We may employ a commutator moved by the action itself, by imparting to it the necessary movement, by means of an electro-magnet, placed in the circuit, and which is so arranged that, when its power diminishes by the weakening itself of the current, its armature, in detaching itself, causes the commutator to act. Mr. Grove found an advantage by interposing between the pair and the voltameter two large plates of platinum, plunging into diluted sulphuric acid, which, without liberating visible gas, are polarised by the current. It is upon these plates that the commutator acts, so that it is their electro-motive force that is added to that of the current, which causes the latter to travel always in the same direction, in the voltameter properly so called. Three experiments made with a single nitric acid pair gave in the same time in the voltameter,—

	Cub. in.
Without platinum plates interposed.	0 146
With plates interposed - -	0·097
With plates and commutator -	0·225

The increase of effects, due to what Mr. Grove calls *voltaic reaction*, is therefore very sensible.

Among the causes that diminish the resistance to passage in a voltameter, we have pointed out* the heating and shaking of the electrodes, and more particularly of the negative electrode. M. Beetz has succeeded in demonstrating that the effect of these two actions is due to the fact, that they diminish or destroy the polarisation of the electrodes. He has remarked that, when the current is feeble, the destruction or diminution of polarisation by heating is, as I had already observed, more sensible for the negative electrode; but that it becomes the same for both, when the current is powerful; which is due to the circumstance that the electro-motive force of the electrode, polarised by the hydrogen, is very su-

* Vol. II. pp. 74. and 409.

perior to that of the electrode polarised by oxygen; whence it follows, that the difference between them, in this respect, must be more sensible with the current, and consequently the two polarisations are feeble. Moreover, the influence of temperature over the polarisation of the electrodes must vary, not only with the force of the current, but with the nature of the electrodes themselves, and of the electrolytic liquids placed between them.

It remains for us, therefore, before terminating this paragraph, to treat upon some points, that are connected with it. We must first mention a new class of gaseous pairs, discovered by M. Gaugain, when making some researches on thermo-electricity, and which we have already pointed out in passing. The most simple of these pairs is that which is obtained by putting in presence of each other at an elevated temperature two tubes of glass which contain, one air, the other the vapour of alcohol. M. Gaugain has succeeded in producing with these pairs, which may be arranged end to end, so as to form a true pile, all the effects of ordinary hydro-electric pairs. He recognised that the nature of the wires, that are employed for placing the glass tubes into communication, either with the ground or with the condenser, does not influence the results, and that these wires consequently play merely the part of simple conductors. By forming a series of gaseous pairs with air, oxygen, nitrogen, carbonic acid, hydrogen, vapours of water, alcohol or ether, M. Gaugain found those alone to be active, in which one of the two elements was air or oxygen, and the other one of the elastic fluids, differing from these two gases. He took care to stop the tube with glass at both ends, when he filled it with an elastic fluid, other than air, or one of the vapours. He is disposed to conclude, from his researches, that the electricity arises simply from an action, that is exercised between the oxygen and the glass, that is brought to a state of fusion; and that the second elastic fluid plays only the part of a simple conductor. We should be rather disposed to believe, still admitting the action of the oxygen upon the melted glass, that the phenomena observed by M. Gaugain enter altogether

* Vol. II. p. 423.

into those of Grove's gas pile, with this difference, that the electrolytic liquid, which separates the two elastic fluids, is melted glass, instead of being a solution of sulphuric acid; now, that melted glass can serve as an electrolytic liquid, is what Buff's recent experiments demonstrate, who not only has obtained its decomposition by a voltaic current, but has even succeeded in employing it in this quality in the construction of a pile.

Another point upon which we have yet to speak, is the property discovered by M. E. Becquerel that hydrogen possesses under the influence of platinum, of bringing about the reduction of a solution of chloride of gold; which neither hydrogen alone, nor platinum alone, are capable of reducing.

A small test tube, about $\frac{1}{10}$ of an inch in diameter, filled with hydrogen gas, is placed in a vessel, containing a solution of chloride of gold, so that it plunges into it by its open extremity. At the end of some days, if the temperature has not sensibly varied, the level of the chloride of gold in the interior of the tube, remained very nearly the same; but if a platinum wire is introduced below the test tube, so that the wire is situated in part plunged in the hydrogen gas, and in part plunged by its other extremity in the chloride of gold, we then see the volume of gas to diminish in the interior, and even at the end of a certain time to disappear entirely, if the platinum wire goes to the top of the tube. At the same time that the hydrogen disappears metallic gold is precipitated upon the portion of the platinum wire, that plunges in the metallic solution. This action is manifested in closed tubes, and in which there is no trace of atmospheric air; the effect is not due to the action of the liquid upon the platinum, since platinum alone does not exert it, and no trace of platinum remains in the solution after the operation. If a gold wire is substituted for that of platinum, the reduction of the chloride in the hydrogen no longer takes place. This effect is evidently the result of a local action, that is to say, of a molecular current, which sets out from the particles of hydrogen, adhering to the surface of the platinum, at the spot where

this metal touches the surface of the solution of chloride of gold, traverses a small film of this solution, goes and abuts on the part of the platinum, which, being plunged into it, is no longer covered with hydrogen, and deposits gold upon it. The affinity of hydrogen for chlorine is here sufficient of itself alone to bring about the formation of the voltaic circuit; and consequently the electrolysation of the solution.

Finally, it remains to us to speak of a phenomenon, that we have already mentioned in passing *; and which consists of that peculiar state, that iron is able to acquire, by virtue of which it becomes unattackable by acids, and is able to play in many cases the part of platinum; a state which M. Schœnbein, who has made a very special study of it, has designated under the name of *passivity*, calling the iron that is possessed of it, *passive iron*.

Bergmann and Kirwan had already remarked that iron, employed for precipitating silver from its solution, loses this property at the end of a certain time; Keir showed that the iron employed can no longer precipitate silver, not only from the solution, in which it has been already plunged, but from any other. Braconnot having remarked that concentrated nitric acid does not attack iron, Herschel examined this subject nearer; he observed that soft and cleaned iron, plunged into nitric acid of 1·4, begins by getting brown; then it produces an effervescence, during which the liquid becomes red; all action soon ceases, and the iron has acquired the property of being no longer attacked; a slight friction does not remove from it this property; but it loses it, if it is rubbed too powerfully; it also loses it, if it is touched in an electrolytic liquid with an oxidisable metal. Iron, in this state, is able to resist the action of a very strong acid. But, of all philosophers, M. Schœnbein is the one, who has made the most detailed study of this subject; therefore it is his works, that will essentially direct us.

When one of the extremities of an iron wire is heated to redness, and, after its cooling, is plunged into nitric acid of 1·35 of density, this extremity suffers no action on the part

* Vol II. p. 423.

of the acid, whilst the same acid acts energetically upon the extremity of the iron wire, that is not heated. A passive or inactive iron wire is able to render passive one, that is not so. It is sufficient for this purpose to place them in nitric acid of 1·35 of density, after having placed them in contact, taking care to introduce the passive iron first; the two wires then equally suffer no chemical action; it is the same, when they are separated. We may even render an iron wire passive, which already is suffering a vivid action in nitric acid, by plunging into the acid circuit an iron wire that is already passive, and placing the two wires in contact by their extremities, that are out of the liquid. Platinum, carbon, and all unoxidisable metals, are able as well as iron, already passive, to give by their contact passivity to an iron wire, which does not possess it. A pair of iron and platinum, entirely plunged in nitric acid, does not give any effect, when the acid is gradually heated, except when the acid begins to enter into ebullition; the iron is then attacked, and is not long in being dissolved.

Passive iron may remain a long time, thirty days and more, in nitric acid, without losing its property of not being attacked; it preserves it, when it is well drawn from the acid, even when it is exposed to the air, or is plunged into pure water, or into ammonia; but as soon as its surface is rubbed, it becomes active again.

A passive iron wire enjoys all the properties of a platinum wire; thus it may be used as a positive electrode in a pile in any acid solution, both sulphuric and nitric, and oxygen is liberated upon it in the desired proportion; whilst the liberation of hydrogen takes place at the negative electrode, which is platinum. Thus again, like platinum, it no longer precipitates copper, and the oxidisable metals, from their respective solutions; a property, to which we shall return in the Chapter of the Seventh Part, which will be devoted to the chemical applications of electricity. When the pile is a simple one, composed of a single pair, if a wire of passive iron is employed as a positive electrode, whilst a platinum wire is its negative electrode, there is no decomposition, on

plunging the two wires in a solution of sulphuric acid; whilst there is a powerful liberation of hydrogen around the platinum wire, when ordinary iron or oxidisable metal is taken for the other electrode. We may in like manner momentarily produce this liberation of hydrogen, by placing for a moment in contact in the liquid passive iron, which forms the pair iron and platinum with an oxidisable metal, such as zinc, tin, copper, and even silver; but the liberation of gas that then takes place upon the platinum, endures for a few seconds only.

We may even render an iron wire passive, by employing it in water acidulated with sulphuric acid as the positive electrode of a powerful current, produced by a single pair, and the negative electrode of which is of platinum. The decomposition of water no longer takes place in a sensible manner; but if we touch for an instant the iron electrode with that of platinum in the liquid itself, the decomposition takes place vividly, as soon as they are separated from each other, to cease an instant after. The same effect is produced by touching the iron with an oxidisable metal in the same liquid. But the most curious fact is that, if we unite, exterior to the liquid, the two wires, that serve as electrodes, by a copper wire, a very momentary liberation of hydrogen is then obtained, as in the preceding case, at the moment when the copper wire, by which the two electrodes were united, is removed. The copper wire must not be more than two or three inches in length, and about $\frac{1}{20}$ in. in diameter. When it is longer or thinner, a liberation of hydrogen is obtained during the same time that is employed for uniting the electrodes; and this liberation increases in proportion as the wire is elongated, until it is a little more than five yards in length. At the moment when the copper wire is removed, which established communication between the electrodes, the liberation of hydrogen becomes much more active than it was, while the communication existed; but it does not last long, and the decomposition stops. When the copper wire is excessively long, in such sort that it does not probably transmit more than a very minute proportion of the current, things

take place, as if the electrodes were not united by a conducting communication.

All these effects, and many others into the details of which it is impossible for us to enter, and which, for the greater part, have been observed by M. Schœnbein, are evidently due to the property, that is possessed by iron of covering itself with a pellicle of oxide, which renders it unattackable by certain acids. It thus enters into the phenomena of secondary polarities, which are equally due to deposits, brought about upon the surface of metals. Faraday, who was the first to put forth this opinion, remarks that in fact all circumstances, that are proper for rendering iron passive, are those which must bring about the formation of this superficial film of oxide; such are its heating, its voltaic combination in an electrolytic liquid with a non-oxidisable metal. It would appear that this film of oxide cannot form salts with acids; and consequently has no tendency to combine with them; which would explain why they do not attack iron, that is covered with it, which conducts itself either chemically or voltaically, as platinum. Thus, we have seen, that acidulated water cannot be decomposed with the current of an ordinary simple pair, if the two electrodes are of platinum; for this purpose, it is necessary that the positive metal be attackable by the electrolytic liquid. Now, passive iron wire not being attackable, decomposition does not take place, if it is employed as a positive electrode. But, if this iron is united voltaically in the liquid with an oxidisable metal such as zinc, a liberation of hydrogen is brought about upon its surface, which must deoxidise it, and consequently restore its ordinary chemical activity. It is easy to explain, in the same manner, M. Schœnbein's curious experiment which we have related above. When the powerful current has traversed the acid solution by means of two electrodes, the negative one being of platinum, and the positive one of iron, the latter has become passive by the first liberation of oxygen, that has taken place upon its surface, and the decomposition is stopped. The two electrodes were then united by a thick and short copper wire, that is to say, by a

very good conductor; this wire served at the same time to conduct the current and to form a pair between the two electrodes; this pair, when formed, has destroyed the passivity of the iron, and the water has been decomposed; but when the conductor is suppressed, the current begins to pass again between the two electrodes, water is decomposed at the first moment, the iron then becomes passive again, &c. If the copper wire, by which the electrodes are connected, is too long, the phenomenon no longer takes place, because the wire becomes too bad a conductor, either to derive the current, which continues to pass in great part between the electrodes, or to permit the latter to form a current sufficiently active, in consequence of the imperfect communication, that is established between them; that which proves that this influence of length concerns only the diminution that it occasions in the conductibility of the wire, is that the same result is obtained on making use of a short and thin wire of a badly conducting metal, such as iron or platinum.

We might perhaps ask *how*, when forming a pair with iron and platinum, that have served as electrodes, we may restore to the iron its activity, as we do by placing it in contact with an oxidisable metal in the liquid; this is due to the circumstance that platinum plays the same part, that zinc or any other oxidisable metal would have played, by the effect of the polarisation that has been imparted to it by the same current, that has rendered the iron passive. This current, in carrying to the iron the oxygen that has determined the formation of the film of oxide, to which the passivity is due, has developed upon the platinum an equivalent film of hydrogen; whence it follows, that this metal, afterwards in contact with the positive iron, becomes the positive element of the pair, which liberates upon the platinum, by decomposing the water, oxygen, which depolarises it, and upon the iron, hydrogen, which deoxidises the surface of this metal, and thus restore to it its chemical activity.

M. Martens had attributed the passivity of iron to a physical modification, that this metal would have undergone, of a nature to change its voltaic relations; M. Schœnbein, still considering that this modification consists only in an

alteration, imparted to the iron, as far as concerns its chemical properties, did not seem to presume that this alteration arises from the formation of a peculiar oxide. It is to M. Beetz, that we are indebted, for having placed beyond doubt the existence of this film of oxide in iron rendered passive; he has demonstrated, contrary to M. Martens, that the blue colour, which is acquired by iron, when heated, is due to the formation of a slight film of oxide; and he has shown that, if this film is sometimes formed in hydrogen at a red heat, it is due to the decomposition of the water that is contained in this gas *; so that if we succeed in having the gas perfectly dry and perfectly pure, colouration no longer takes place, even at a very high temperature.

M. Beetz satisfied himself, by heating an iron wire in a metallic bath, taking care to prevent the wire from retaining a film of air adhering to its surface, that this wire is not passive, and that it is even positive, when it forms a pair with a very polished iron wire. He has demonstrated, by multiplied experiments, made with great care, that it is sufficient to rub or to wash in an acid an iron wire, that has been rendered passive by the action of heat or by that of nitric acid, in order to destroy its passivity; because we thus remove from it the pellicle of oxide, to which this passivity is due. It is easy to explain, by the formation or the reduction of this film of oxide, all the various phenomena that are presented by iron, with regard to its chemical passivity and activity, when it is employed as an electrode in an electrolytic liquid. It is thus that when a pair is formed in nitric acid of 1·40, with an ordinary iron wire and a passive iron wire, the latter renders the former passive, as a platinum wire would have done, by determining a current, that slightly oxidises it, whilst it is itself deoxidised. It then becomes active in its turn; and it is the latter that has been rendered passive; the phenomenon begins again, the two wires having thus changed

* This very colouration, that iron assumes at a very high temperature in hydrogen gas, disappears at a less elevated temperature, by the reduction which the hydrogen causes the film of oxide to suffer.

parts, and it can be renewed indefinitely in the same manner.

Bismuth, nickel, and cobalt are susceptible of becoming passive, like iron, either by the effect of heat, or by the effect of their employment as positive electrodes in the electrolytic decomposition of acidulated waters. Mr. Andrews, who was the first to demonstrate the passivity of bismuth, obtained it by placing this metal in contact with platinum in nitric acid of the density of 1·40; it is merely necessary, in order to procure a passive surface of bismuth, to fill a copper tube with bismuth in fusion, and to make a section in the button thus cooled; plunged into nitric acid of 1·40, this section is not attacked. It is evident that the passivity in this case, as in that of iron, is due to the formation of a thin film of oxide upon the surface of the metals; a film which is formed even upon bismuth, at the ordinary temperature, as is proved by the coloured tints of this metal. M. Beetz had already proved the passivity of nickel; it has been confirmed by M. Nickles, who has also established it for cobalt. He has found that, in order that the passive state of these two metals may be stable, it is not sufficient to plunge them in nitric acid of 1·40; that they must be blued in the spirit-lamp or upon a charcoal fire, and be plunged while still glowing into this acid.

It is therefore evident that passivity is only a phenomenon, purely electro-chemical, arising from the impossibility, in which the oxides of certain metals are found, when they are only at a feeble degree of oxidation, of forming salts with nitric or sulphuric acid. It follows, from this defect of affinity, that the metals in question cannot form voltaic pairs with platinum; a new proof, as M. Schœnbein remarks, of the part played by chemical affinity in the production of voltaic electricity, and a new argument consequently against the contact theory. Regarded in this manner, passivity is nothing more than the effect of the presence of a thin film of an heterogeneous substance (a pellicle of oxide) upon the surface of a metal; which justifies the place we have given to the study of it in this paragraph.

A last electrical phenomenon, that arises from the deposit of very thin heterogeneous films upon the surface of metals, is that of the production of electric currents by the action of light upon these deposits, when they are of a peculiar nature. M. E. Becquerel has in fact obtained very decided electric currents by bringing about chemical actions, by means of light upon metallic plates of platinum; for example, those covered with an impressionable film, such as a film of chloride, iodide or bromide of silver. A plate thus prepared is plunged into acidulated water with another plate also of platinum, but whose surface is perfectly clean; and they are made to communicate each with the two ends of a galvanometer. As soon as a ray of light is made to act upon the impressionable film, an electric current is brought about, in which the plate covered with this film, acquires positive electricity, as peroxide of lead would have done; — an affect due to the combination with the hydrogen of the water, under the influence of light, of the chlorine, bromine or iodine of the film, with which the platinum plate is covered; and consequently to the chemical decomposition of this film. M. E. Becquerel has taken advantage of this property for constructing, under the name of *electro-chemical actinometer*, an apparatus which enables him to appreciate with the greatest sensibility, the energy with which the rays of light act upon a chemical combination, and consequently of comparing, under this relation, the rays of various refrangibility and the modifications, that are imparted to them, by their passage through screens of various natures. The solution in which the two plates are plunged, is a diluted solution of sulphate of soda; the two plates are of silver; the one is cleansed, and has a very clean surface; the other is covered with a film of a particular sub-chloride of silver, which is violet, and which, of all impressionable films, is the one, that is the best, because it gives to the galvanometer an electric effect, that bears a relation to the chemical action produced.* It has, moreover, the

* This sub-chloride is produced by employing the silver plate, upon the surface of which we desire it to be found, as positive electrode, in hydrochloric acid; care must be taken to employ a current of only a feeble intensity.

property of receiving coloured impressions on the part of all the luminous rays equally; and moreover to acquire of itself a tint, similar to that of the ray, that has acted upon it: it is a kind of inorganic retina. We cannot here enter into the details of the construction and preparation of M. Becquerel's apparatus, and of the different parts, of which it is composed, nor yet into the exposition of the results that he has obtained by employing it; this would be going beyond the limits that we have assigned to ourselves, seeing that the properties of light would be in question and not those of electricity; for it is here only the means employed to obtain an apparatus, intended for quite another class of studies.

Production of Electricity in Combustion; and by the combined Action of Heat and Chemical Affinity.

When once it is well proved that every chemical action gives rise to electricity, it is evident that combustion, which is one of the most decided of chemical actions, must also liberate it. The study of the electric state of flame has attracted the attention of philosophers from the very earliest time, that electricity was the object of attention. It is especially under the relation that it exercises over bodies already electrised, by drawing off from them their electricity, and becoming charged with it, that flame has been regarded. Dufay, Winkler, Watson, Franklin, Priestley had already made many experiments upon this power of flame. Humboldt had not found in this respect differences between different species of flames, such as those of an oil wick, a taper, phosphorus, hydrogen, and sulphur. He attributed the action of the flame to the conductibility of the various substances, that emanate from it, such as carbonaceous particles, vapour of water, carbonic acid, &c. Volta, who was greatly occupied on this subject, thought that the property of flame of discharging electrised bodies, was due to the current of air, that it brings about, and to the circumstance, that at the same time it renders the air a conductor, by heating

and rarefying it. We have seen * that Riess, after having analysed with great care the faculty of flames and substances in combustion, such as carbon, of drawing off electricity from bodies that are charged with it, had demonstrated that they act like a multitude of small points; but, for this purpose, it is necessary that the filaments of vapour, which are formed in combustion, as well as the molecules that play the part of points, shall be of a conducting nature such for example, is the case with the vapour of water, and with particles of carbon.

In studying the conducting power of bodies in combustion, it was not long before it was seen that it presents anomalies. Thus, it had been remarked that carbon, when its combustion is moderated, discharges unequally positive and negative electricity, and that it is the same with Davy's aphlogistic lamp †; which is not due, as Ermann had thought, to a peculiar property of incandescent platinum wire, but rather to the points of vapour, which arise from this wire. It is positive electricity that Davy's lamp transmits better to a conductor in contact, whilst it is negative, which is most easily communicated, under the same circumstances, by a point of carbon in combustion. We are about to see that this inequality of action in the conducting property for the two electricities in these two cases is only apparent, and is due to the circumstance, that in one and in the other, there is an actual production of electricity by the effect of combustion.

Volta had already made evident the electricity liberated in the combustion of carbon, by using, for bringing about this combustion, only a feeble current of air, in order that it might not be too energetic; for, without this precaution, the electric signs were scarcely sensible. But it was M. Pouillet, who was the first to prove, by decisive experiments, the production of electricity in the combustion, either of carbon or of hydrogen. He found, conformably to what takes place in the

* *Vide* Vol. II. p. 149.

† It is known that, in Davy's aphlogistic lamp, a platinum wire, coiled into a helix, is retained incandescent by the vapour of alcohol, which burns on its surface; a phenomenon, which is due, as we have seen above at p. 412. to a series of oxidations and reductions, that the platinum wire undergoes.

development of electricity by chemical actions, that the carbon is charged with negative electricity, and the carbonic acid, that escapes from it, with positive electricity. In order to obtain this result, he cut into a cylinder a piece of good conducting carbon; then, after having lighted one of its extremities, he placed it by the other end upon a plate of metal in communication with the upper plate of a condenser; he then blowed upon the carbon, by means of a bladder, filled with air, in order to retain the combustion in its upper part alone; the lower plate being placed in communication with the ground, he succeeded in charging the upper with negative electricity. In order to collect the positive electricity with which the carbonic acid is charged, it is necessary to place the carbon cylinder at a little distance below the plate of metal, that communicates with the plate of the condenser, taking care to place it itself in communication with the ground. The carbonic acid yields its electricity to the plate, in proportion as it rises against its surface. In the combustion of hydrogen, the oxygen is electrised positively, and the hydrogen negatively. In order to collect the negative electricity of the hydrogen, a metal tube, which is put in communication with the condenser, is adapted to the bladder, that contains it, and at the extremity of which the gas is lighted; or rather a long platinum wire is adjusted to the plate of the condenser, the extremity of which is coiled into a narrow spiral, which is plunged carefully and entirely into the interior of the flame. The positive electricity of the oxygen is collected by presenting the same platinum spiral at some distance from the flame; it is necessary to take the precaution of giving it a greater diameter than that of the flame, so that it may envelope it. It may even take, at a distance $\frac{1}{10}$ of an inch or so, the positive electricity, with which the surrounding air is also charged. It is more probable that it is the vapour of water, and not the oxygen, which, in the combustion of hydrogen, acquires positive electricity, as the carbonic acid acquired it, in the combustion of carbon.

The electric phenomena, that accompany combustion, are less simple than would appear, according to the results ob-

tained by M. Pouillet; it is especially in the electricity, that is liberated by flame, that these anomalies are sensible. M. Hankel satisfied himself, by means of a platinum plate, placed above the flame of a spirit lamp, that the latter is charged with positive electricity, provided the lamp is in communication with the ground: it is necessary for the lamp to be of metal; if it is of glass, a platinum wire is placed at the bottom of the wick, or in the alcohol, and which is put into communication with the ground. The negative electricity is collected by putting into communication with the condenser, either this wire or the lamp, and placing the platinum plate, that is above the flame, in communication with the ground; these conditions are indispensable, in order to obtain electric signs. By taking, as with a species of gauge, by means of platinum wires buried in glass tubes, and the extremity of which alone is bare, electricity from the different parts of the flame, M. Hankel found the tensions very different. With a small flame of hydrogen gas, coming out from a brass stop-cock, which is in communication with the ground, he obtained signs of positive electricity, which went on increasing in intensity, in proportion as the platinum that drew it off, approached the extremity of the flame, and which was at its maximum at the extremity itself. The effects were similar, only the electricity was of a contrary nature, when the platinum plate communicated with the ground, and the stop-cock with the condenser.

Besides signs of tension, M. Hankel obtained electric currents, by causing the wire of a galvanometer to communicate on the one part with a lamp, on the other part with a plate of platinum, placed above the flame; the current was directed in the flame from above downwards. It is necessary, in this case, in order to the currents being a little powerful, that the combustion shall have as much vivacity as possible. This is the reason why the platinum plate must be held, not horizontally, but a little inclined above the flame. The presence of metal is not indispensable for the success of the experiment; a moist conductor, even the moistened hand, may be substituted for it. In order to be satisfied as to the

part, which a variation in the conductibility of the flame itself, may take in the intensity of the current, M. Hankel introduced into the circuit the current of a small pair, in such a manner, that it was led in a direction contrary to that of the current of the flame; the first current being constant, it was easy to prove, from variations in the effect observed, that the intensity of the latter did increase with the extent and the vivacity of the combustion. A very extraordinary fact, observed by M. Hankel, is that the flame of hydrogen gives results precisely contrary to those of the flame of alcohol, whether we study its electric state by means of the condenser, or prove it by means of the galvanometer; thus the current travels from below upward in the hydrogen flame, when the circuit is closed, instead of travelling from above downwards, as with the flame of alcohol.

Becquerel, who already, before the researches of Pouillet, had studied the electric state of the flame of alcohol and of that of hydrogen, had arrived at believing that the phenomena of combustion is not the only cause of the electricity liberated. He had remarked that conducting wires or plates acquire negative or positive electricity, which they communicate to the flame, according to the degree of temperature, which they acquire, on being heated by it; he had concluded from this that flame exercises an electro-motive action upon the bodies, that enter into contact with it, and that consequently metallic plates or wires, that are plunged into it, do not play simply the part of conductors. M. Hankel's experiments are not of a nature completely to refute this idea, since this philosopher is still obliged, in order to collect the electricity, to place the flame in contact with heterogeneous bodies, even when these are, instead of metals, moist conductors or the hand.

M. Buff, who has made a very particular study of the electric nature of flame, arrived at a similar result. After having proved by delicate experiments that air, hydrogen, carbonic acid, and the vapour of water, are very bad conductors up to 752°, he has succeeded, by heating them to a still more elevated temperature, in causing them to be traversed by the current of two Daniell's pairs; he has found more-

over, that these gaseous bodies, when they are at a very elevated temperature, may develope electricity in other conducting bodies, both solid and gaseous, placed in contact with them. But he has constantly observed, on plunging the two ends of the platinum of the galvanometer into the different parts of the flame, that the current went from the most heated wire to that, which was least so; whence he has concluded that the effect was due to a thermo-electric current.

However, when he employed the condenser, Buff has obtained positive electricity on touching with a platinum wire in communication with the condenser, the exterior part of the flame, and with the negative, penetrating into its interior part; this result is independent of the temperature of the wires, which would give a contrary effect, of a nature to diminish the intensity of that which is observed. The bodies of lamps, when they are of metal, draw off the negative electricity from the interior part of the flame, if they are put into communication with the ground; whilst every conductor, such as a plate of metal, moist wood, or even the moistened hand, draws off the positive electricity from the exterior part. If with an alcohol lamp, we obtain an effect contrary to that which is obtained with hydrogen, as Hankel has observed, this is due, as Buff has also proved, to the circumstance that the metallic conductor is in contact with the wick, and consequently is found moistened with alcohol; it is then the thermo-electric effect of the metal which predominates, the wire that is covered with alcohol being necessarily less hot than the other. Also, instead of touching with the wick the wire that is introduced into the interior of the flame, as soon as it is raised a little higher, it is no longer seen to produce the exceptional fact. Thus then we may regard it as established that every flame, that of a spirit-lamp as well as that of an oil lamp, or that of hydrogen, disperses into the exterior air, by which it is surrounded, positive electricity, as soon as the negative electricity from the interior is conducted to the ground. All these phenomena, according to M. Buff, are thermo-electric effects, in which the gases and vapours, are as much acting

bodies as metals are; they have not consequently any relation with the chemical phenomena of combustion; also, this philosopher lays it down as a principle that, when a thermo-electric circuit is closed with air, hydrogen or the vapour of alcohol, carbon or metal, an electric current is developed, which moves through the air, from the hotter place of contact to the less hot.

The researches of M. Buff, like those of M. Hankel, leave therefore the question still undecided of knowing whether the electricity that is obtained, on introducing solid bodies into flames, has a purely thermo-electric origin, or whether it depends, if not in totality, at least in part upon the phenomenon of combustion. Mr. Grove has endeavoured to solve it in the following manner. He employs two platinum wires, six inches in length, and about $\frac{1}{50}$ in. in diameter, which are both coiled into helices at one of their extremities, whilst they communicate by their other extremity, by means of an insulated copper wire, with the wire of a sensitive galvanometer; one of the small helices is placed entirely in the yellow part of the flame of a spirit lamp, submitted to the action of the blowpipe, very near to the summit of the blue cone, and the other helix is arranged near to the orifice of the air current, at the base of the blue cone, or root of the flame; the two helices are at a distance of about two inches from each other. The helix that is in the full flame arrives at the red-white state of incandescence, the other, which is at the origin of the flame, is only cherry-red. The galvanometer indicates a deviation of 6°, the helix that is near the orifice playing the part of the zinc or the positive metal, in this species of pair, in respect to the other, which plays the part of negative metal.

It is easy to prove that the effect observed is not due to a thermo-electric current developed at the points of junction of the wires of platinum and copper; for it is not altered, when only one of these points of junction is heated by a spirit lamp. Moreover, the slight thermo-electric current, that may be thus obtained, travels in a contrary direction to the current in question, which may be clearly proved; and

moreover the thermo-electric current requires, in order to be collected, a short wire galvanometer, whilst a long wire galvanometer is necessary for the other. Nor is it a thermo-electric current, due to the unequal heating of the two platinum helices; for, the helix, that is in the yellow plume, may be withdrawn, so that it is less heated than that which is at the base of the flame, without changing with this the direction of the current. If the helix, that is at the base of the flame, be brought beside that, which is toward the summit, the deviation of the galvanometer diminishes; but it preserves its direction until the wires have become very near; — a case, in which the current of the flame gives place to the thermo-electric current, the direction of which depends upon which of the two helices is most heated.

Wires of zinc, iron, copper were substituted for one of the platinum wires; the current equally took place, but more powerfully, when the oxidisable wires were in the full flame and the platinum wires at the base of the flame, than in the reverse case. This difference is probably due to the circumstance that, the oxidisable wire being thicker, they produced, when they were in the full flame, an effect of cooling, which facilitated the development of a thermo-electric current, moving in the same direction as the current proper of the flame.

We may obtain a much more decided effect by uniting the simultaneous action of these two currents. Mr. Grove has obtained this, by forming with a platinum plate a small cone of a little more than $\frac{1}{5}$ of an inch in depth, and of as much in width, and substituting this little cone, suspended in a platinum ring, for the helix placed in the full flame; the other helix being still at the base of the flame. The small cone must be filled with water; and the water is renewed by pouring it in drop by drop from a pipette. Mr. Grove has thus succeeded in obtaining a deviation of the galvanometer, of 20°, and even of 30°, the direction of which was the same as that of the deviation, that had been obtained in his former experiment. When the cone full of water was placed at the

base of the flame and the helix above, the deviation was not more than 5°.

Mr. Grove concludes from his researches, that there exists in flame a true voltaic current, that is completely independent of thermo-electricity, which leads him to regard this current as the result of the production of electricity, which takes place in the phenomenon of combustion, as is proved by the experiment, by which M. Pouillet charges a condenser with negative electricity, by causing a piece of carbon to burn upon its surface. In the experiments, that precede, the platinum, that is at the base of the flame, where chemical action commences, plays the part of the zinc of the pair; and the platinum which is above, where the combustion, and consequently the chemical action is terminated, the part of the negative metal or conductor.

The cause why this current proper, due to combustion, could be observed by Mr. Grove in a manner very distinct from the thermo-electric current, is that the employment of the blowpipe, by giving to the flame a very determinate direction, readily separates the portions, in which the combustion operates from those in which it is operated, whilst in ordinary flames, these portions are mingled, and circulate in a confused manner one among the other.

M. Becquerel, notwithstanding Mr. Grove's experiments, has persisted in not seeing, as did Buff, in the electric currents liberated in flame, anything else than thermo-electric effects. He remarks that, if one of the ends of the platinum is plunged into the alcohol of the lamp, maintained at 32° by melting ice, and that fixed to the other extremity of the galvanometer is a cylinder of platinum also filled with ice, no current is obtained, on placing this cylinder in the interior of the flame, until the ice which it contains, being melted, the cylinder is able to become heated,—a proof that the current is thermo-electric. That is true in this case; but it does not follow from this, that an electro-chemical current may not exist, when, instead of placing the platinum plate or wire in the alcohol, it is placed in the flame at its very base; a condition necessary, in order that this current may be

established, as we are about to see. M. Becquerel places still symmetrically the two platinum spirals s and s′, in the same horizontal section of the flame F, of a spirit-lamp L (*fig.* 319.), so as to attain red temperature; and in this case there is no current; but if, by means of a second lamp and the blowpipe, one of the spirals is heated to red-white, a current is produced, which goes from the cherry-red spiral to the red-white spiral. The current has therefore a direction the inverse of that which it possesses, when one of the spirals is in alcohol at the ordinary temperature, whilst the other is in the flame, with a temperature, which does not exceed incandescence; which would prove that the thermo-electric properties of platinum would change at elevated temperatures. Another manner of proving the same result consists in placing the two spirals, held by means of two supports, which permit of their being raised up or brought down (*fig.* 320.), one at the visible extremity s′ of the flame

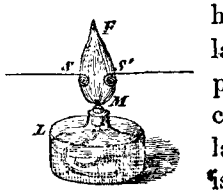


Fig. 319.

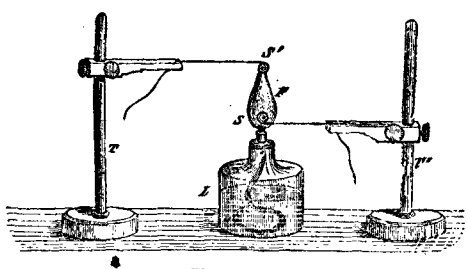


Fig. 320.

F, the other at its base s, in its blue part, and at a distance of an inch from the former. There is produced a current which goes from below upwards in the flame; on successively raising the lower spiral to a distance of an eighth of an inch or so from the upper, the current increases in intensity; and this augmentation is still more considerable if the upper spiral is heated with a second lamp and a blowpipe. The fact that there is no current when the two spirals, being placed in the exterior envelope of the flame, are at the

same temperature, and we have merely to heat one of them powerfully, without changing their place, in order to obtain a current, leads M. Becquerel to conclude that the current is thermo-electric, and that it must be the same as that, which is obtained with the two unequally heated spirals, placed one at the summit, the other at the base of the flame; the more so as the positive state of the one, that is at the summit, s increased by heating it more. But in his manner of bringing about the heating, M. Becquerel introduces a great modification into the experiment, by introducing the action of a second flame, which may play another part than that of simply heating the spiral.

We therefore believe that, notwithstanding the ingenious experiments of M. Becquerel, we must admit, with Mr. Grove, that there are two currents in the flame; one thermo-electric, the other due to a chemical action. With regard to this latter, M. Matteucci appears to us to have found its veritable cause.* When a flame of alcohol or of hydrogen, which comes to the same thing, is in question, the following is what takes place: one of the plates is in contact with the oxygen of the ambient air, the other with the hydrogen; these two plates are separated by a film of aqueous vapour formed by combustion; we have thus therefore, a veritable gas pile like that of Grove, with this difference, that the electrolyte here is vapour of water. The direction of the current is perfectly in accordance with this explanation; and we see why M. Becquerel obtains no effect by placing one of his spirals in alcohol, or placing them both in contact with the exterior part of the flame, and consequently with the oxygen. When he heats one of them with the dart of the blowpipe, it is evident that he places it in contact, no longer with the

* M. Matteucci, in his researches on the electricity of flame, commences by determining the electric conductibility of different flames, by employing them for transmitting the current of two Daniell pairs, by means of two platinum wires. When the wires are not more than about $\frac{1}{10}$ of an inch distant in the flame of a lamp with a double current of air, he perceives that the flame begins to be conducteous, probably by a cause similar to that which causes the current to be transmitted through the gases elevated to a high temperature in the experiments of M. E. Becquerel (p. 160.). The flames of wax and of stearic acid are sensibly more conducteous than those of alcohol, if we take care to prevent the formation upon the platinum wires of a film of black matter, which prevents the transmission of the current.

air, and consequently with oxygen, but rather with hydrogen or the vapour of alcohol of the new flame; it must therefore render it positive, as indeed actually take place. In support of his explanation, M. Matteucci cites a great number of experiments, at first those by which he has proved, by means of a platinum spiral, that he causes to communicate with the condenser, that no electric sign is obtained by directing upon it different parts of a well insulated flame of hydrogen; whilst if by still holding it plunged in the flame of hydrogen, a similar one is placed in communication with the ground, at an inch or an inch and a half above it, marked and constant signs of negative electricity are found in the electroscope, analogous to those, which would be given by a plate in contact with hydrogen in one of Grove's gas pairs, the other plate of which would be in contact with the oxygen and would communicate with the ground. By causing the latter spiral to communicate with the condenser, and the former with the ground, decided signs of positive electricity are obtained. If spirals of blackened, or platinated platinum are employed, the effects are the same, only more powerful. By substituting oxidisable metals for the platinum plates, less distinct electric signs are obtained; and the phenomena become complex, because a part of the electricity liberated must arise from the decomposition of the vapour of water by these metals, heated to redness. In support of the analogy, which he establishes between the phenomenon of the electricity of flame, and that of the electricity, produced in a gas pair, M. Matteucci cites an experiment, in which he has obtained very strong signs of electric tension, by placing two plates of platinised platinum, one in hydrogen, the other in oxygen, the two gases being enclosed in two bell-glasses inverted in the same trough, which was itself filled with water, either pure or slightly acidulated, into which the two plates partly plunged.

In order to prove the existence of secondary polarities in the platinum wires, that plunge into the different parts of the flame, M. Matteucci places two platinum wires, so that they may be in contact, one with the interior of the flame of a spirit-lamp,

and the other with its surface or with its point; the deviation of the galvanometer indicates that the current goes in the flame from the base to the point. The flame is extinguished; the wires are allowed to cool; the circuit is then closed with water; a very strong current is obtained, moving in the same direction, as that which was obtained, before the water had been substituted for the flame. These two currents are therefore evidently due to the same cause; and, if the former is more feeble, it is due to the imperfect conductibility of the flame, or rather of the vapour of water, which suffers electrolytic decomposition on the part of the hydrogen and the oxygen, adhering respectively to the two plates of platinum, between which this vapour is interposed.

Mr. Grove, still admitting the ideas of M. Matteucci, on the origin of the electro-chemical current of flame, does not think that it is the water in the state of vapour, that plays the part of an electrolyte, but rather the flame itself, which would form an electro-chemical chain, in which each particle of the carbon or the hydrogen would combine with the neighbouring particle of oxygen, and so on, bringing about a series of combinations and decompositions, with excess of oxygen at one of the extremities of the flame, and excess of carbonated hydrogen at the other. However, nothing proves that vapour of water at a high temperature cannot suffer an electrolytic decomposition; the phenomena of the electro-chemical polarity of gases discovered by Grove himself, that we have described above*, are altogether as legitimately favourable to this supposition, as we shall see further on, as are other facts relative to the part played by the vapour of water in the production of the electric phenomena, attributed to contact, and in its conducting property for electricity.

M. Matteucci explains in an analogous manner the origin of the electricity, that is liberated in the combustion of carbon; he remarks with justice, that the form and position of the carbon are indifferent to the success of the experiment, which M. Gaugain has confirmed †: but he adds, what is

* Vol. II. p. 464. and following pages.

† M. Gaugain finds that he succeeds very well in charging a condenser with negative electricity, by means of the combustion of carbon, by taking care to

equally exact, that, in order for the experiment to succeed, it is necessary that the air be moist; moreover, in ordinary carbon, there is always hydrogen, which burns with the carbon itself; and consequently there is formation of water. This water is decomposed by the incandescent carbon, as it would be by a heated iron crucible, into which it might be projected; and by its decomposition it must render the carbon negative, whilst the hydrogen and carbonic acid carry off the positive electricity. The point upon which the learned Italian insists, in favour of his theory, is that it is impossible to find signs of electricity in the combustion of pure carbon in dry oxygen gas, no more than in that of the metals, such as iron and zinc; whence he concludes that, in order to there being a development of electricity, the decomposition of an electrolyte is necessary, and that the simple combination of two elements is not sufficient. We shall examine further on the extent to which this opinion is founded.

Before terminating this paragraph, we shall say a few words upon a particular class of currents, that M. Becquerel has designated under the name of *pyro-electric*, and which are also, like those of flame, due to the combined action of heat carried to a high degree, and to chemical affinity. These currents are produced whenever metallic substances are in contact with vitreous substances in the state of igneous fusion, or at any rate softened by heat. If, into a furnace filled with glowing coals, is introduced a rod of soft iron and one of copper, each in connection with one of the extremities of a galvanometer, no current is obtained; whilst one is obtained, if the copper rod is enveloped in a glass-tube, provided that the temperature is raised to the point of fusion of this glass. The current increases in intensity in proportion as it is heated, setting out from the point where the glass softens; then, when the point of fusion is arrived at, the current attains its maximum and remains constant.

select a very good conducting piece of carbon, then to light it; and, after having placed it in communication with the plate of the condenser, to place at about $\frac{1}{10}$ in. from the lighted surface a spiral of platinum, or any other conductor that is made to communicate with the ground. At the commencement it is necessary for some time to excite the combustion with a pair of bellows.

The current goes from the iron to the copper through the carbon and the glass. The iron oxidises and the copper remains intact, as would have taken place in a hydro-electric pair.

The liberation of the electricity has therefore a purely chemical origin, merely excited by heat; for if, when the glass which surrounds the copper, being partially melted, it happens that this metal touches the iron, there is no longer any effect, contrary to which would happen, if the current were thermo-electric. A similar effect is obtained by substituting for the iron a piece of gas-carbon cut into a cylinder, which suffers a veritable combustion.

In order to obtain more decided, and more durable effects, M. Becquerel places in an earthen crucible a plate of copper, which he covers with powdered glass, into which he causes a rod of iron to penetrate; he then places the crucible in a reverberating furnace. He succeeded equally well in producing a strong and constant current, by introducing two long rods, one of iron, the other of copper, into a crucible filled with pounded glass, to which he adds 0·25 of carbonate of soda, in order to facilitate fusion. Although other vitreous substances may play the same part as glass, the latter has appeared preferable in all the trials that have been made.

M. Buff, on his part, at the end of experiments upon the conductibility of heated glass, succeeded in constructing a pile, in which the electrolytic liquid is replaced by glass. He placed one above the other, and in the same order, discs of gilded brass, discs of cleaned zinc, and thin plates of glass; he then attached platinum wires to the first disc and to that which covered the tenth plate of glass; the pile thus formed was an inch and a half in height. The plates were pressed against each other, so as to be able to be subjected to the current of hot air of an argand lamp. This pile, at the end of a little time, was able to produce a divergence of $\frac{2}{3}$ of an inch in the gold-leaf electroscope. When the discs were heated, a contact of a few seconds produced a divergence of at least an inch and a half. A similar pile, and which had

been frequently used, had lost nothing of its primitive electro-motive force, at the end of five months.

Applications of the preceding Principles to the Construction and to the Theory of the different Voltaic Piles.

We have established in a general manner the theory of the voltaic pile in the first paragraph; but we were not able, before having completed the study of the liberation of electricity in the various forms that chemical actions assume, to appreciate all the causes, that may influence the power of this apparatus, nor indicate the modifications, by which they may be increased. Now that this study is complete, it is easy for us to make a detailed analysis of all that takes place in a circuit of which the pile forms a part, and to find the means of giving to its action all the energy, of which it is susceptible.

A closed voltaic circuit may be regarded, as we have already remarked, as a system of conductors, in which the electricity is propagated by a series of decompositions and recompositions of the electricities of their consecutive molecules. These decompositions and recompositions of the electricities are accompanied, in the electrolytic liquids, that are used for charging the pairs of the pile, and in those which are found in the voltameters, when there are any in the circuit, by the decomposition and recomposition of the molecules themselves. The action is the same or equivalent in each pair and in the voltameter, as is proved by experiment; and the only difference is, that the pair contains one or two bodies, which, by virtue of the chemical affinity for the elements of the liquid, with which it is charged, determine the formation of the polar chain, which continues in the voltameter, only because the polarity is transmitted into it by the intervention of the electrodes and metallic conductors by means of which they communicate with the pair. We may therefore consider voltameters as inactive pairs introduced into the circuit, and we should remark, that their introduction weakens the current, not only because it occasions one resistance more, as the introduction of any additional

conductor would do; but because it creates an electro-motive force, contrary to that of the voltaic pair or pile itself. Indeed, as soon as a voltameter or inactive pair is interposed in the circuit, the decomposition of the liquid, with which it is charged, brings about a secondary polarity, upon the surfaces of each of its electrodes;—polarities, the effect of which is to produce a current, moving in a direction contrary to that which has determined them. It is therefore an electro-motive force, created by the action itself of the current, which must be deducted from the electro-motive force of the pair or the pile, when we desire to recognise the real electro-motive force of the current, that traverses the circuit.

But it is not only in the voltameters, that this contrary electro-motive force is developed; it is also produced in the pairs themselves, when the circuit is closed for a few moments. Indeed, in each pair there is an active metal, generally zinc, and an inactive metal, platinum or copper; while the circuit is closed, the zinc oxidises; it then dissolves to the state of sulphate, supposing that the exciting liquid is a solution of sulphuric acid, at least so long as the liquid is still acid, and is not saturated with the sulphate; but the platinum or copper, becoming covered either with hydrogen or with zinc or oxide of zinc, arising from the decomposition first of the acidulated water, then of the dissolved sulphate. Now, these deposits impress upon the metal upon which they take place a secondary polarity, the effect of which is to give rise to a current, moving in a direction contrary to that of the current, that would be produced by the action of the zinc upon the liquid, and consequently would notably diminish this latter. As these secondary polarities are produced equally upon the inactive metal of each pair, they are added to each other, as the electro-motive actions of the zincs are added; and the latter, in certain cases, may be sufficiently reduced as to end by becoming null. Then the pile no longer exerts action; this happens to piles that have been for some time in action, as all experimenters have recognised; among whom we will cite M. Marianini, who has made a series of the

experiments upon the weakening that voltaic piles suffer, whilst their circuit is closed during a longer or shorter time; and upon the time during which their circuit must be left open, in order that they may recover the whole or part of the force, that they have lost. In general, it is in the first moments, when the circuit has just been closed or opened, that the diminution or increase of power is the most decided; then a moment arrives, when the power of the pile no longer diminishes or increases, a very important fact, and one which would have placed M. Marianini in the way of the cause of the phenomena, that he had observed; in that the weakening takes place in a pile, only so long as its circuit is closed; and that it is even sufficient that its poles be not well insulated, in order to its being manifested. It varies with the nature of the pairs, and principally with that of the inactive metal. M. Marianini has remarked that it had also taken place with dry piles, the poles of which were united by a band of lead. Two Zamboni's piles of 1500 pairs each, having had their poles thus united, at the end of a minute their tension, measured by the divergence of the leaves of the electroscope, was seen to descend from 14° to 6°; and at the end of 20 minutes to 2°. The circuit having been opened at the end of 21 minutes, the tension had returned to 14°. Repeated and rapid contacts produce the same effect as a continuous communication. Finally, it is easy to restore to a pile the force that it had lost, by causing it to be traversed by the current of another pile, but guided in a direction contrary to its own. All these effects are a natural consequence of the polarisation, that is brought about upon the inactive plates of the pair by the deposits arising from the electrolytic decomposition of their liquid; — deposits, which disappear at least in part, by the dissolving action of the liquid, when the circuit is open, and which are still better destroyed by the formation of deposits of a contrary nature, that are determined by an inverse current, transmitted through the pile. It is easy to satisfy oneself of the accuracy of this explanation by closely examining these plates, and employing them for forming pairs with plates similar, but which have not been

used; they play all the parts of the positive metal, in respect to these latter.

The effect that is produced upon the current of a pile, by the interposition of metallic diaphragms or inactive pairs, between its pairs, is due to the same cause as that, which arises from the polarisation of the inactive metals, or the plates of a voltameter; a voltameter being, as we have said, itself merely an inactive pair, interposed between the two metals of an active pair. Also the influence of the nature of the substances, of which the inactive pairs are made, explains very well the diminution, which their interposition causes the current to undergo, being in relation to the facility which they possess of retaining the deposits that are formed upon their surface; thus those upon which the liquid exercises a chemical action, scarcely stop the current at all, because the deposits are dissolved, in proportion as they are formed. Moreover, we have already demonstrated that here was the veritable cause of the resistance to passage, by experiments, by means of which we have proved that this resistance is weakened, and becomes even null, when we employ alternate currents, succeeding each other very rapidly, with which the formation of the deposits is impossible.*

One of the causes that most contribute to diminish the secondary polarity of the inactive plates of the pairs of which a pile in action is composed, is the presence of oxygen. As far back as 1801, Pepys, and more recently Biot and Cuvier had shown, by placing a column-pile surmounted by a bell-glass, that there was absorption of oxygen, if the poles of the pile were united; and that in vacuo or in nitrogen, the current of this pile was greatly weakened. This influence of oxygen had been attributed to the circumstance, that its presence facilitates the oxidation of the attackable metal of the pair; but latterly, Mr. Adie, and after him M. Viard, have demonstrated, by accurate and numerous experiments, that it is by its action upon the negative or inactive plate of the pair, that the oxygen exerts its influence. Thus, when

* Vol. II. p. 402. and following.

two plates of the same metal are placed, one in boiled water, and the other in water, that contains oxygen in solution, the two liquids being separated by a porous partition, it is always the latter plate, that is negative, in regard to the former. This result, in accordance with those, which we have seen to have been already obtained by Matteucci and by Grove, explains in the same manner that the establishment of the current in the gas pile, the polarisation of the successive molecules of the liquid, and their decomposition and recomposition, are facilitated by the presence of oxygen upon one of the plates, which determines the direction of the polarisation, and consequently that of the current. But the influence of oxygen is much more marked, when the pairs are formed of two different metals; this M. Viard has proved with various voltaic combinations, such as *zinc* with *platinum, silver, copper, and iron; iron* with *platinum, silver, and copper; copper* with *platinum and silver;* and finally, *silver* with *platinum.* Different liquids were employed for electrolytes, care being taken, in each case, to place them in two compartments, one of which contained the liquid, deprived as much as possible of oxygen, whilst the other contained the same liquid aerated with oxygen. The experiments were made in the same manner as when the plates were homogeneous, that is to say, by plunging one of the plates into the liquid deprived of air, and the other into the aerated liquid; it was always the presence of the oxygen on the negative plate, which increased the force of the current;—an increase due evidently to the absence of secondary polarity for this plate, on account of the absorption brought about by the oxygen for the nascent hydrogen, in proportion as it is liberated upon its surface by the current.

In order to measure and compare the absorption of the oxygen that takes place in pairs of different natures, M. Viard combined his apparatus, so that the electrolyte might be screened from contact with the air; then, placing above each of the elements of the pair, a small graduated bell-glass, filled with oxygen, he was able to determine the absorptions, both in the case, in which the circuit was closed,

and in that in which it remained open. The pairs, successively submitted to experiment, were *zinc platinum, zinc-silver, zinc-copper,* and *zinc-iron* pairs; the electrolytes were successively, with each pair, pure water, solutions of sulphate of potash, and of chloride of sodium; the experiments lasted from twenty to twenty-five days with pure water, and only sixteen hours with the other liquids. The following is the result of the absorption, measured by the elevation of the liquid, in the tube filled with oxygen, for two of the pairs, chosen at the two extremities of the scale: —

Electrolyte.	Zinc-Platinum.		Zinc-Iron.	
	Closed circuit.	Open circuit.	Closed circuit.	Open circuit.
Water - -	18·0	3·0	14·0	12·0
Sulphate of potash -	33·5	0·5	16·0	8·0
Chloride of sodium -	9 ·0	0·5	14·0	7·5

We see that the difference between the absorption, when the circuit is closed, and the absorption, when it is open, is greater with saline solutions than with pure water; it is the more considerable, as well as the absorption itself, as the negative plate is less oxidisable. The absoption does not take place at the negative plate only, but it equally takes place at the positive, with this difference, that it remains then sensibly the same, whether the circuit of the pairs is open or closed. The absorption at the negative plate must depend upon the intensity of the current; it also varies with the nature of the pair and with that of the electrolyte. With a zinc-iron pair, charged with pure water, and which consequently is very feeble, the opening of the circuit has no influence over the absorption, the latter taking place almost exclusively upon the positive plate, whilst with a zinc-platinum pair, charged with a solution of sulphate of potash, and the current of which is very powerful, which permits of a very short experiment, the absorption is considerable, when the circuit is closed, and almost null when it is

opened, seeing that then it is taking place upon the positive plate alone.

It follows therefore from all that precedes, that the cause of the sudden and great reduction, which voltaic piles suffer, when their circuit has been closed for some moments, is not so much the diminution in the exciting faculty of the liquid with which they are charged, that is to say, in the energy of the chemical action exercised upon the oxidisable metal, as the creation of a contrary polarity upon the negative or inactive metal, by the effect of deposits arising from the electrolytic decomposition of the liquid, principally of hydrogen.

Let us now see how, setting out from these principles, we may be able to give a satisfactory explanation of the properties, that characterise each species of pile, and more particularly the constant current piles. We shall not return to the details of the construction of the diverse voltaic piles; —details, which we have set forth in the Second Chapter of our First Part; we will regard them as known in the analysis, that we are about to make of the circumstances, that influence the power of these apparatus.

The first column-piles *, as well as those in the wooden troughs, the *couronne des tasses*, the trough of pipe-clay or of copper †, are, as may be remembered, composed of zinc-copper pairs, charged with a single liquid, namely, an acid or saline solution. All present the inconvenience of becoming very rapidly enfeebled when their circuit is closed, by the effect of the polarisation of their negative plates. This inconvenience is reduced, either by taking as an exciting liquid a solution of sulphuric acid, in which a little nitric acid is mixed, or in giving to the negative plates a much greater surface than to the positive. These two modifications, introduced into the first modes employed for charging and constructing the pile, had been introduced empirically, experience having pointed out the advantages of them; now, it is easy to comprehend the utility of this, by remarking,

* Vol. I. p. 30. (*fig.* 17.).

† Vol. I. p. 36. (*fig.* 25.); p. 37. (*fig.* 26.); p. 38. (*fig.* 27.); p. 39. (*figs.* 28. and 29.); and p. 40. (*figs.* 30. and 31.).

that the presence of nitric acid in the exciting liquid facilitates the partial solution of the deposit upon the negative plate, and that the extent, given to this plate, diminishes on each part of its surface the quantity of this deposit.

To these perfections, Faraday had added some others; he had, as Dr. Hare had first * pointed out in his calorimeter, approximated the zinc and the negative metal (copper or platinum) as near as possible to each other, contenting himself with separating the two metals, in order to avoid all contact between them, by a sheet of paper. Moreover, as in Wollaston's pile †, the copper goes around the zinc, and a piece of wood or cork prevents the lower part of the copper from touching the lower edge of the zinc plate. Not only are the zincs very near to the coppers in each pair, but the pairs themselves are also very near together; and their coppers are also preserved from metallic contact by several sheets of paper. But the greatest modification introduced by Faraday is to plunge the whole pile into the same liquid, and not each pair into a separate cell. Without doubt, the effect is a little enfeebled; because a part of the electricities is recomposed through the liquid, which bathes equally all the pairs; but this recomposition is very feeble in respect to that which takes place through the conductor, that unites the two poles of the pile, provided that the exciting liquid is not too acid a solution, and consequently too conducting. Experiment has shown that there was no sensible difference, as far as concerns the incandescence of wires, which requires the employment of good conductors, between two piles of forty pairs exactly similar, except that in one the exciting liquid was in cells separated for each pair, and that in the other it was in a single trough. Moreover, the employment of this pile is very convenient, seeing that nothing is more easy than to immerse and to withdraw promptly the metal pairs, which causes very little zinc to be consumed, and the pile to occupy very little space, on account of the proximity of the plates of which it is formed. As the zinc plates are

* Vol. I. p. 40. (*fig.* 30.).
† Vol. I. p. 39. (*fig.* 28.).

very thin, they may be made of rolled zinc, which is very superior to cast zinc. MM. Young and Munch have modified Faraday's pile by substituting amalgamated zinc for the ordinary zinc, and so arranging it, that each zinc is always situated between two surfaces of the same copper; the whole combined so as to occupy the least possible space, so that in Munch's pile fifty pairs occupy scarcely a length of twelve inches.

Smee's pile, like that of Faraday, is also a pile in which there is only one liquid interposed between the metals of the pairs, but the zinc in it is amalgamated, which avoids all local action, and the negative element is covered with a film of finely divided platinum, as are the platinised platinum plates of Grove's gas pile. This latter circumstance facilitates singularly the liberation of the hydrogen, and consequently the development of the electro-motive force of the pair, by diminishing or almost entirely annihilating the secondary polarity of the negative metal. Thus a same plate of amalgamated zinc, placed successively in contact in diluted acid, with platinised platinum and polished platinum, heated to drive off the air from its surface, liberates in one minute for the former five times as much hydrogen gas as for the latter. All the other effects of the current are increased in the same proportion. Mr. Smee, in his pile, places the platinised plate between the two vertical faces of a plate of amalgamated zinc, as in Grove's nitric-acid pile; but as there are neither two liquids, nor any porous cell, he greatly approximates the two faces of the zinc, by giving to his pairs the form of those of the Wollaston pile.* The platinised platinum plate may, without inconvenience, have only $\frac{2}{3}$ of the size of the faces of the zinc plate.

Smee's pile is generally charged with a solution of 1 part sulphuric acid for 7 of water. Its effect is much more constant than might have been expected from a pile of a single liquid; and with an equal number of pairs of equal surfaces, it possesses a very superior effect to that of a Daniell's with sulphate of copper. Smee, as a motive of economy, employs,

* Vol. I. p. 39. (*fig.* 28.)

in his pile, platinised silver, instead of platinum; but silver, on account of its polish, submits badly to the operation of platinising. On this account, M. Boquillon has devised the employment of a plate of copper, upon which he first deposits a coat of copper, so that it is rough and covered with asperities; he then covers this first coat with a coating of silver, which participates in the same superficial state; and it is upon this film of silver that he finally deposits pulverulent platinum, which, by adhering to it, gives to the plate in the highest degree the property of liberating hydrogen freely.

M. Poggendorff has also succeeded in giving to pairs, formed of a plate of amalgamated zinc and a plate of copper, plunged into diluted sulphuric acid, a remarkable force and constancy, by covering the copper plate with a pulverulent coat of copper, similar to that of platinum, with which Smee covers his negative plates.

But the surest manner of avoiding all polarity upon the negative plate is to plunge it into a liquid, which absorbs the hydrogen at the moment when, and in proportion as it is liberated *, and which also prevents a deposit of zinc or oxide of zinc upon this plate, arising from the electrolytic decomposition of the salt, which is formed in the action upon the amalgamated zinc of the liquid, which attacks it. Daniell was the first to conceive the idea of this perfection by making application to the construction of the pairs of a voltaic pile of the electro-chemical effects, that take place in two liquids, separated by a porous membrane, and which M. Becquerel had already discovered and described. This philosopher had in fact already observed, both in his oxygen-gas pile, as well as in a pair formed of two plates, one of zinc, the other of copper, plunged into two distinct compartments, filled with various exciting liquids and separated by a diaphragm of gold-beaters' skin, that much more constant currents may be obtained than when a single liquid is employed. Thus he had obtained a rather strong and tolerably constant current,

* Another advantage of the absorption of the hydrogen is to avoid the mechanical obstacle, that the appearance of the bubbles of gas opposes to the free circulation of the current.

by putting nitrate of copper into the cell where the copper was, and sulphate of zinc into that where the zinc was; with sulphuric acid very much diluted with water in both cells equally, and a few drops of nitric acid in the copper cell, he had succeeded in producing a rather constant effect, due to the action of the nitric acid, as we have already remarked, when speaking of the advantage that he had recognised when charging old piles with a solution of sulphuric acid containing a little nitric acid.

Daniell has then contrived to construct a pair, and consequently a pile, in which, still leaving the zinc in a solution of sulphuric acid or of common salt, he plunges the copper into a concentrated solution of sulphate of copper; the two liquids are separated by a porous diaphragm, made of an organic substance, such as bladder, gold-beaters' skin, close-woven cloth, or wood, or simply formed of unglazed and unvarnished earth. We have already given the description of this pile.* We shall therefore confine ourselves to producing here (*fig.* 321.) a sulphate of copper pair, such as Daniell constructed originally. A B is a cylinder of copper, which serves at the same time as vessel and as negative metal; the two bases of this cylinder are pierced, at E F and at *a b*, by two circular openings, to which is strongly attached by its two extremities a tube of porous membrane, which is nothing more than the intestine of an ox, properly prepared, in the interior of which is placed a cylinder of amalgamated zinc, C *d*. From the lower opening to the centre of *a b*, there comes out a syphon tube *c f g*, intended to give escape to the liquid contained in the membranous cylinder, when fresh is added to it. Care must be taken to maintain at the top of the solution of sulphate of copper some crystals of this salt, in order that it may always remain as concentrated as possible. Notwithstanding certain advantages, that this mode of construction might at first seem to present, the

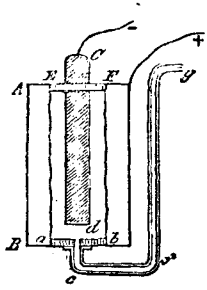


Fig. 321.

* Vol. I. p. 42.

system, that we have described in our First Volume, is very generally preferred.*

Daniell's pile, like all other in which the zinc is amalgamated, presents the advantage that there is no chemical action when it is not working; but that which characterises it essentially is that its effect is constant, because the copper does not polarise. Indeed, when the current is closed, the hydrogen that results from the decomposition of the acidulated water upon the surface of the zinc, meeting the sulphate of copper beyond the porous membranes, combines with the oxygen of the first molecule of this sulphate, so that it is the sulphate that is now decomposed†, and that it is its copper which goes and deposits itself, forming a thin film of copper upon the copper of the pair; the latter therefore is not altered, and consequently not polarised. It is true, that when the solution of sulphate, being a little exhausted, has become tolerably acid, it is then the acidulated water, and no longer the sulphate, that is decomposed; whence it follows, that hydrogen is liberated upon the surface of the copper; but so long as there remains any sulphate in the solution, this sulphate is reduced by the nascent hydrogen, and it is still a deposit of copper, that is obtained; only it is granulous, instead of being united, brilliant, and ductile, which already diminishes a little the force of the current: then, when the solution is entirely exhausted, hydrogen is deposited upon the copper itself, and then the current loses its constancy. On this account it is of great importance to maintain the solution of sulphate of copper, as much as possible in the state of saturation. The useful effect in the Daniell's pile is entirely in the action of the zinc upon the exciting liquid, by which it is bathed; for copper exercises no sensible action upon its sulphate, as is proved by experiment; the decomposition of this sulphate cannot therefore be an electric source; but simply the effect

* There is an advantage in the Daniell's pile, in which the copper and the sulphate of copper are always placed exteriorly, in giving to the zinc cylinders, that plunge into the porous tubes, filled with a solution of sulphuric acid, the form of hollow cylinders, instead of that of solid cylinders, in order that they may present more surface to the action of the liquid.

† *Vide* Vol. II. p. 386.

of the current produced by the reunion of the two electricities liberated upon the zinc; — an effect, which, by the deposit of copper, that it occasions, produces the constancy of the apparatus.*

M. Buff has introduced into the Daniell's pile a modification that gives to it a remarkable constancy, and one, that is very precious for researches, which, without requiring a great force of current, requires that this force shall remain as constant as possible for a tolerably long time. This modification consists in constantly renewing the sulphate of copper, and at the same time causing the amalgamated zinc to bring itself in its liquid, only in proportion as it is used, which is obtained by means of a counterpoise.

Things do not take place exactly in the same manner, with the Grove's pile, in which nitric acid is substituted for the sulphate of copper, and consequently platinum for the copper (*fig.* 322.). Besides, the nitric acid, being a much

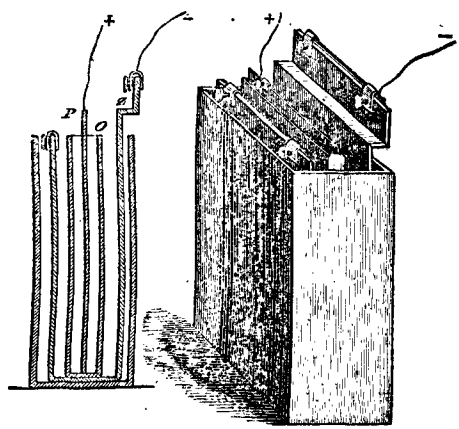


Fig. 322.

better conductor than the solution of sulphate of copper, the current is more easily transmitted, it is probable that in this case the facility with which the nitric acid abandons its

* See Vol. I. p. 43. (*fig.* 32.) In *fig.* 34. the zinc and platinum are connected metallically by a thin plate of brass, furnished with hooks and screws, so as to form a clip. In *fig.* 33. of Vol. I. they are simply united by a clip of wood or of cork.

oxygen, tends to decompose the acidulated water, by taking from it its hydrogen; it is sufficient indeed to plunge into a solution of sulphuric acid two plates of platinum, after having taken the precaution of first moistening one of them with a film of nitric acid, to obtain a powerful current, in which the latter plays the part of the negative metal. Thus then not only does the nitric acid, in preventing by its contact with the platinum plate the deposit of nascent hydrogen and consequently secondary polarity, render the current constant, but at the same time it contributes to increase its intensity, as does peroxide of lead and substances in general, which contain much oxygen. A real inconvenience of Grove's nitric-acid pile is, that its constancy does not last long; if its circuit is closed for a few moments in succession without interruption, providing the conductor that connects its poles is good, nitrous vapours are seen to escape from the porous vessels in which the nitric acid is contained; this acid itself changes colour, and becomes boiling, and it is then necessary to stop the action of the pile. This inconvenience may be mitigated by mixing a little concentrated sulphuric acid (one-half or one-third) with the nitric acid, or even taking, instead of nitric acid at 1·40, nitric acid mixed with one-half of water. But the current loses in intensity what it gains in constancy, especially if the latter means is employed; for with the former, which is much preferable, the force is not sensibly diminished. It has even been proposed to substitute peroxide of manganese, mixed with concentrated sulphuric acid, for the nitric acid; but satisfactory results are not obtained by the process.

Bunsen's pile, in which carbon is substituted for platinum *

* Vol. I. p. 46. (*fig* 34. and *fig.* 35). M. Silliman employs as carbon, in Bunsen's pile, natural plumbago, or artificial plumbago, such as that of which crucibles are made. Mere pieces of coke, well selected, may also be advantageously employed.

The following, however, is M. Bunsen's mode of preparing his carbons:—An intimate mixture is first prepared, of one part of pitcoal (by weight), and two parts of coke, in impalpable powder. This mixture is introduced into a cylindrical mould of sheet iron, in the centre of which is placed a small roll of card $\frac{1}{4}$th of an inch in diameter, so as to form in the carbon an internal cavity, and facilitate the liberation of the gases during calcination. Thus filled with the mixture of carbon, and closed by means of a movable cover, well adjusted, the iron mould is heated to redness, until all liberation of gas has ceased. After this

(*fig.* 323.) does not present, in the same degree, the inconvenience, that we have been pointing out in Grove's pile. This

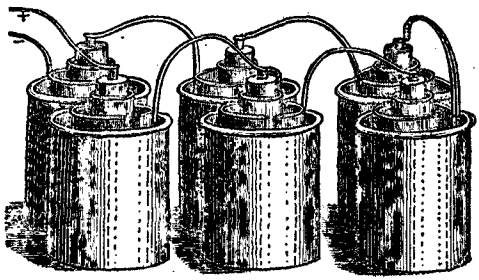


Fig. 323.

is due to the circumstance that carbon, not being so good a conductor as platinum, the current that results from the closing of the circuit is less violent. However, at the end of a certain time, only a little longer, which is due also to the circumstance that the mass of acid in it is generally more considerable, nitrous vapours are seen to rise, and the acid to enter into ebullition. It is also necessary to take the precaution of not introducing pure nitric acid, but rather to mix it with water. We may even content ourselves with plunging the carbons, when they have sojourned a long time in nitric acid, in a solution of sulphuric acid, with which the porous tubes are filled. The nitric acid, with which the carbons are impregnated, suffices for a tolerably long time to

calcination, the carbon is easily withdrawn from the mould in a compact form, cylindrical like the mould, very hard, and susceptible of submitting to the action of the file and the saw without breaking. The lathe may give to these cylinders the suitable form. This being done, it is well to steep several times over the cylinders of carbon in a concentrated solution of molasses, and to submit them to a fresh calcination as intense as possible. Many elements may be calcined together in a large earthen or iron crucible, the interstices being filled with pulverised coke.

Finally, before plunging the carbon into the nitric acid, it is indispensable to cover with a film of melted wax the neck, upon which is adapted the metallic ring, or rod intended for establishing the necessary communication between the carbon and the zinc, in order to prevent the acid from coming and corroding the metal by the effect of capillarity. After each experiment, the nitric acid may remain without inconvenience in contact with the carbons. The cell containing the sulphuric acid must, on the contrary, be removed, emptied, and washed in plenty of water, as well also as the zinc cylinder.

increase the power and to maintain the constancy of the pairs.*

This property of carbon has served me for constructing a pile in which oxygen itself may, up to a certain point, be substituted for nitric acid. I introduced (*fig.* 324.) into a porous tube, in the centre of which is a platinum wire, carbon well baked, and consequently a good conductor, reduced into an impalpable powder. I took care to ram it well; then I placed the porous tube thus filled in the interior of a cylinder of amalgamated zinc, which is itself plunged in the solution of sulphuric acid. A pile of eight or ten pairs, constructed in this manner, and the zinc cylinders of which were only 2 in. in height and $1\frac{1}{2}$ in. in diameter, gave me for eight days, without interruption, a decomposition of acidulated water, not very strong, about $\frac{1}{10}$ of a cub. in. per minute, but very constant. The hydrogen which would have polarised the carbon in each pair disappears, by its combination in the nascent state with the oxygen, that the carbon retains in its pores, and which it takes from the atmospheric air. When the pile is weakened, a few drops of nitric acid poured upon the upper face of the rammed cylinder of carbon, revives it for a tolerably long

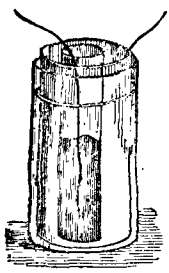


Fig. 324.

* M. Callan has had the idea of substituting lead for the platinum and the carbon in Grove's and Bunsen's piles; and he has obtained very satisfactory results. But he has found great advantage in covering the leaden plate with a slight film of platinum or of gold, by means of the chlorides of these two metals. It is evident that there would be a great economy in employing for Grove's piles plates of copper, or lead platinised, intead of plates of platinum. M. Schœnbein had also the idea of employing, as a negative metal, passive iron, and as a positive metal ordinary iron, the former being in contact with nitric acid, and the latter with the solution of sulphuric acid. It is very curious to see the same metal, iron, play at the same time the part of negative and of positive metal. However, in this latter relation, amalgamated zinc is very preferable; but hollow cylinders of cast iron, the inner side of which has been rendered passive, may very well serve, at the same time, as negative metals of the pair, and as vessels into which the nitric acid is placed; then the porous tube, filled with the solution of sulphuric acid, into which the iron, or rather the amalgamated zinc, is plunged. I have for a long time advantageously used piles thus constructed.

Mr. Callan has also latterly made use of cast iron for constructing with amalgamated zinc, a single liquid pile, charged with a mixture of sulphuric acid and a saline solution. He has obtained very good effects from this arrangement.

time. But a moment arrives at which the sulphate of zinc, having penetrated into the powder of carbon, it is necessary to dismount the pile, in order to wash the powder in plenty of water, or, which is more simple, to change it. I have found, that we might in this pile substitute with advantage, for the platinum wires, small cylinders of carbon, of about $\frac{1}{3}$th of an in. in diameter, prepared like those that are used in the Bunsen's piles, taking care to place them in the axis of the porous tubes, before surrounding them with the powder of carbon, and planting in them a copper wire, intended for establishing communication.

Wheatstone, as we shall see in a moment, has successfully employed, in his researches, pairs in which there is only one liquid, but avoiding the immediate contact of the positive metal with this liquid. This metal is dissolved in mercury, so as to form a liquid amalgam; the amalgam itself is placed in a small porous tube (*fig.* 324.), and the tube is plunged in the solution, that bathes the negative metal; sulphate of copper, if this negative metal is copper; chloride of platinum, if this metal is platinum. A wire of copper or of platinum is plunged into the amalgam, in order to draw off the negative electricity. The chemical affinity, that is exerted upon the oxygen, or upon the chlorine of the solution, by the positive metal, the zinc for example, dissolved in the mercury, is sufficient to bring about the production of a current, which is tolerably constant*; less however than in piles of two liquids; for a little metallic copper is soon perceived in the amalgam, against the interior side of the porous tube, when the solution is sulphate of copper, which is due to the local action of the zinc upon the sulphate, which reduces a little copper.

In all two-liquid piles, and even frequently in those, in which there is but one liquid, we are therefore led to employ diaphragms or porous tubes, which, while preventing the mixture of the substances that they separate, allow, by their being moistened, of the electric communication being

* It is necessary, that the salt in solution be a salt whose base is the same metal as the negative metal of the pair, in order that the voltaic current, in decomposing it, may not alter the nature of the surface of this negative metal.

established between them. These diaphragms, as we have seen, are of different species; and it is not useless, before terminating that, which concerns the details of the construction of the different piles, to say a few words upon them.

Goldbeaters' skin and bladder, on account of their little thickness, are the diaphragms, that oppose the least resistance to the passage of the current; but chemical agents promptly destroy them, and they possess the inconvenience of facilitating too much the endosmose of the liquids, which on this account cannot remain long separated. Also this species of diaphragms, which may be good in certain experiments of delicate researches, must be rejected in the construction of piles in common use. Leather and tanned skin possess the same inconveniences, but in a less degree; however, the preparation, which they must be made to undergo, sometimes alters them so much, as to render them unfit for the service for which they are intended. Sail-cloth is better, seeing that it has only a feeble degree of endosmose on neutral solutions; it is necessary, when the form of a bag is given to them, that the seam be made with a thread covered with pitch. Paper or pasteboard, tarred, a little permeable to liquids, is a tolerably good diaphragm; the tar prevents the paper from dispersing in the water. But, in fact, of organic diaphragms, those which are made of thin wood are perhaps preferable to all. Thus, for Daniell's pile, hollow cylinders of lime wood, with very thin sides, have constantly given me very good results. It is necessary to take the precaution, in order to remove the resinous matters which are found in the wood, especially when it is pine that is employed, to plunge them for a long time in boiling alkaline water; then they must be preserved, when not in use, in water slightly acidulated; otherwise they shrink and split in drying, which renders them unfit for the object in view.

Inorganic diaphragms are generally of clay, or, better still, of kaolin; this latter, deprived of carbonate of lime, forms in the state of paste a diaphragm, to which much thickness can be given, which is advantageous for avoiding endosmose, provided that it is well saturated with a good conducting liquid, and that it is not too closely pressed. But it is especially under the form of vessels, either prismatic as in Grove's piles,

or cylindrical as in those of Bunsen, that inorganic diaphragms are serviceable. They are made in general of unglazed porcelain, but they present more resistance than half-baked earth and than crucibles. These latter are very convenient, because they may be easily procured; only it is necessary to diminish with the file the thickness of their sides, which generally is too considerable. Care must be taken to wash frequently all these diaphragms, in order to remove the salts which, penetrating and crystallising in their interior, end by causing the sides to burst. We must also watch that these diaphragms contain neither carbon, pyrites, or other substances of a metallic origin, which, being conducteous, might establish between the two liquids, that are separated by the diaphragm, a communication of quite another nature to that which we have in view; that is to say, a metallic communication, which would bring about an electro-chemical decomposition: it is to the presence of these heterogeneous substances, that may be attributed the appearance, that sometimes occurs on the surface of the diaphgrams of reduced metallic deposits. Organic subsances do not present the same degree of inconvenience, but they possess that of producing of themselves the reduction of certain metals, when they plunge into their solutions. To sum up; in practice, it is to diaphragms of unglazed porcelain that the preference has been given, although they present more resistance than others to the passage of the current.

We shall not here dwell upon the description of some other piles, more or less constant, such as those, in which the moist conductor is simply the earth, whether the two metals of the pair are implanted in the moist ground, as Bain, Loomis, and others have done, or they are placed in a vessel filled with earth, which is watered with hydrochlorate of ammonia, as in the Bagration* pile. These different piles having been

* This pile produces a current of an astonishing constancy, which arises either from the reduction of the hydrogen upon the copper, by the compound that the ammoniacal salt forms upon this metal, or by the absorption of the hydrogen by the earth itself, which moreover fills the office of a diaphragm, and thus prevents a deposit of zinc upon the copper. It is well not to place the two plates of the pair too near to each other, and to plunge the plate of copper, before placing it in the earth, in a solution of ammoniacal salt, allowing it to dry, until a greenish film is formed upon the surface.

constructed with a view to applications, the description of them will naturally find its place when we shall be speaking of those applications, to which they relate. We shall, for a like reason, return to them in a subsequent paragraph of this Chapter, in which we shall be treating the question of contact, the theory of dry piles, of which we have already given the description.*

But if, in respect to form, we have nothing to add, as we have said, either in this paragraph, or in the fifth of the Fourth Chapter of our First Part†, it is far from being the same, in regard to the nature of the solid and liquid substances, which constitute the pairs; but this important point is about to be treated in detail in the following paragraph, devoted to the measurement of electro-motive forces, and to the comparison, in respect to their power, of the different voltaic combinations with each other.

However, before entering upon this important subject, we have still to mention a process very different from those which precede, in order to maintain and to increase the power of piles by destroying secondary polarities; it is that, which has very recently been devised by M. E. Becquerel, and which, if it has not all the practical tendency, which one might perhaps have been prepared to expect, is not without its interest in a theoretical point of view. The process consists in giving to the pairs of a pile a tolerably rapid motion in the liquid, by which they are bathed. Thus, M. E. Becquerel has obtained with a single platinum and amalgamated zinc pair, a very sensible increase, by the fact of the movement. This pair at rest in a solution of sulphate of soda, half-saturated, would give to a galvanometer, that was not very sensitive, a deviation of 8°; when it was put into motion, the deviation went as far as 20°. This effect is evidently due to the circumstance that the motion depolarises the plate of platinum; however, there is an advantage in moving also the zinc plate, because the liquid films that bathe its surface are thus charged. If a solution of sulphuric acid is substi-

* Vol. I. p. 53. † Vol. I. p. 36.

tuted for that of sulphate of soda, the effect of the movement is much less decided, on account of the abundant liberation of hydrogen upon the platinum; but it becomes more so when well powdered carbon is placed in the diluted sulphuric acid, so as to make of it a paste. This paste facilitates the depolarisation of the platinum by absorbing the hydrogen, at the same time that it removes it by its mechanical action of friction.

The following is an experiment, that gives the idea of the effect, that the depolarisation of the negative metal of the pairs of a pile may produce, when brought about by means of movement. M. E. Becquerel has arranged a small voltaic pile of ten pairs formed of discs of amalgamated zinc, and of copper 4 inches in diameter, carried by an axis, so as to be able to be set in motion by the aid of a handle. Their surface was parallel, and at a distance of $\frac{1}{5}$th of an inch, and they plunged into troughs in which might be placed a liquid or a pasty mass, so that their circumference might penetrate at a depth of only about $\frac{1}{2}$ an inch beneath the surface of the liquid. Two copper conductors were carried upon two copper basins, soldered to the two discs of each pair fixed on the axis, so that, from the motion of the discs themselves, one of each of them always plunged in the liquid, and the two discs might be made to communicate together.

The pile of ten pairs was employed for decomposing water, and the hydrogen at the negative electrode, was measured by the aid of a measure graduated to the tenth of a cubic centimètre (·006 cub. in.).

Liquid contained in the Cells of the Pile.	State of the Discs.	Volume of Hydrogen in Cent. liberated in 20′.
Water saturated with sulphate of soda - -	Rest - -	6·25
	Motion - -	46·75
Carbon of coke reduced to a liquid paste by water, acidulated by sulphuric acid to $\frac{1}{100}$ - - -	Rest - -	21·00
	Motion - -	136·00

We see that, in consequence of the movement, the effect of the pile has been seven times more considerable.

It follows however from the researches of M. E. Becquerel, that movement, independently of the depolarisation that it brings about, is a means of liberating electricity; thus, of two plates of zinc plunged into a same solution, that which is in motion becomes negative in respect of that in rest, which remains positive; it is the same with other oxidisable metals; with those which are not so, or are less so, it is the reverse. Thus, whether we operate in distilled water, or we employ an acid or a saline solution in a pair composed of two similar elements, platinum or carbon, for example, it is the movable one, that is positive in respect to the fixed; that is to say, which plays in respect to it, the part of attacked metal. In the former case, it is evident that the contact established by the motion between one of the elements of the pair and the oxygen of the air, tends to depolarise it, by taking from it the hydrogen adhering to its surface, and consequently to render it negative; in the latter, it is possible that the oxygen which the movable element takes from the air, aids the liquid into which this element is then plunged, in exercising upon it a chemical action, which gives rise to a feeble current, of which the galvanometer detects the existence. It may also happen that the simple friction, which follows a rather active agitation of this element in the liquid, may be a source of this electricity. However if, on the other hand, the presence of the powder of carbon increases the effect, whilst that of sand in the liquid does not increase it, it is difficult to see in this the effects of friction. We should be rather disposed to attribute all these phenomena, which are a little complicated, to small chemical reactions, which result from the introduction of air into the liquid under the influence of solid bodies in movement. They would be of the same order as those which M. Becquerel sen. had already for a long time studied; such in particular as this curious fact, that when the two ends of the wire of a galvanometer are terminated by two platinum plates, plunging into distilled water, and which are not polarised, if one of them is withdrawn from the water, and is immediately plunged into it again, it determines a current, in which it is positive in respect to the other.

Measure of the relative Electro-motive Force of different Voltaic Combinations.

We have seen*, that the intensity of a current may be represented by the formula $I=\frac{E}{R}$, E being the sum of the electro-motive forces; that is to say, the producers of electricity, which are in action in an electric circuit, and R, the sum of the resistances, which this circuit presents to the circulation of the current. We have subsequently defined the electro-motive force of a hydro-electric pair, the force with which the liquid molecules that enter into the formation of this pair, are polarised by virtue of chemical affinity.† For the present, we will confine ourselves to designating under this name, without making any hypothesis as to its nature, the force that produces the electricity in a voltaic circuit, abstraction being made of the resistance, that this circuit presents. Electro-motive force may therefore be measured, either by the intensity of the current to which it gives rise, multiplied by the resistance of the circuit, $E = I \times R$; or by the static tension of the extremities of the hydro-electric system, the circuit being open. Indeed, from what we have established above‡, the tension of a pair or of a voltaic pile, being only one discharge or one element of a current, since it is always accompanied by a corresponding chemical action, there should be no difference with regard to electro-motive force between the two forms of its manifestation; only, as the velocity with which the electricity is propagated does not exert upon the intensity of its tension (since there is an accumulation of electricity) the same influence as upon that of the current, resistance does not play the same part in the expression of one or of the other intensity. We shall see further on, that we may arrive at exactly the same values, for the expression of the electro-motive force, relative to the different voltaic combinations, in estimating it, either by the intensity of the current, or by that of the tension, to which these com-

* Vol. II. p. 78.
† Vol. II. p. 685.
‡ Vol. II. pp. 676-7.

binations give rise. But as the processes founded upon the estimation of the intensity of the current are of much more easy execution, and more susceptible of accuracy, it is to those, that we shall attach the preference.

The former of these processes is that pointed out by Ohm himself, and which consists in measuring the intensities of the current produced by a same source of electricity, by introducing into its circuit, by the side of the invariable resistance, due to the nature itself of the circuit, two variable resistances; it is easy to conclude from the comparison of these two intensities, the electro-motive force of the source. Let, in fact, $\left(i = \frac{e}{r+l}\right)$ and $\left(i' = \frac{e}{r+l'}\right)$, e being the electro-motive force, r the invariable resistance, l and l' the two additional resistances *, and i and i' the corresponding intensities of the current, measured by the sine or tangent galvanometer, we have, by equating the two values of e, $r+l = \frac{i}{i-i'}\left(l'-l\right)$; whence $e = \frac{i\,i'}{i-i'}\left(l'-l\right)$, by substituting for $r+l$ its value in the value of the aforesaid i. This value of e is given in a function of the difference of the lengths of the wire, or of the additional resistances, that the current surmounts in its circulation.

If we were able to vary the electro-motive force, instead of the resistance, by a known quantity, we should in like manner obtain the value of this force; but this process, which might be practicable for thermo-electric circuits, in which a simple elevation of temperature is sufficient to change this force, is not so for voltaic as hydro-electric combinations, in which we are unable to modify the electro-motive force, without introducing at the same time a change in the resistance.

A second process, employed by Fechner, consists, for comparing two electro-motive forces, in connecting two different pairs whose electro-motive forces are e and e'; so that their

* The resistances are measured by the lengths of wire, as we have explained Vol. II. pp. 80. and 86.

currents travel, first in the same direction, then in contrary directions, then in measuring the sum s, and the difference d of the intensities of their respective currents. We obtain in fact $s=\frac{e+e'}{r+r'}$, and $d=\frac{e-e'}{r+r'}$; whence $\frac{e}{e'}=\frac{s+d}{s-d}$, by equating the two values of $r+r'$. We suppose in this process, that the intensity of the current is proportional to the sum or to the difference of the two electro-motive forces; which follows from the principles, that we have laid down in our First Chapter, and which is moreover in accordance with experiment, as we are about to see. With regard to the resistance of the voltaic combination, which follows from the union of the two pairs, it is evidently the sum of the resistances of each of the two pairs in particular, in whatever manner they may be united.

A third process, likewise practised by Fechner, rests upon the principle that, if the resistances are equal, the electro-motive forces are to each other as the intensities of the currents;—a consequence of the formula, that expresses these intensities. We arrive at this equality of resistances, by adding in the circuit of each of the pairs to their respective resistances r and r', a very great resistance R, in respect to which the other two may be regarded as infinitely small. We may then consider, in the two expressions $i=\frac{e}{r+\mathrm{R}}$ and $i'=\frac{e'}{r'+\mathrm{R}'}$, the resistances $r+\mathrm{R}$ and $r'+\mathrm{R}'$ as sensibly equal, whence we deduce

$$e : e' = i : i'.$$

In order to apply this method, M. Fechner employs a galvanometer with a very long wire, the introduction of which into the circuit of the pair determines this resistance R, infinitely great in respect to the resistances r and r'.

We may add that, in order to measure the intensity of the current, M. Fechner employs the method of oscillations of a magnetised needle, placed in the neighbourhood of the conduc-

tor which transmits the current, a method put in practice for the first time by MM. Biot and Savart.*

M. Poggendorff has made the very just remark, that the application of the three processes, that we have just described, to cases of voltaic combinations, with a non-constant force, and in which, as we have seen, the intensity of the current goes on rapidly diminishing, at least when the circuits are closed, renders all measuring of this current difficult. This is not all; supposing even, that we attain to a state of the current sufficiently constant to enable us to measure it, we shall recognise in the principle itself of the processes a very strong objection against the accuracy of the results, that we desire to deduce from them. Indeed, if we endeavour to determine by the first method, that of Ohm, the electro-motive force e, we find for the expression of this force a value greater in proportion as the absolute resistance is more considerable, which is due to the circumstance, that the pair is weakened so much the less rapidly as the circuit, of which it forms part, is a less conductor; the disturbing causes, such in particular as the polarisation of the negative metal, having so much the less power. The absolute resistance r varies likewise, for the same reason. We therefore conceive that the process is altogether illusory, since the two quantities supposed constant in the formula e and r, vary with the additional resistances l and l', that are introduced. It is true, that this variation of the two quantities e and r, is less considerable, in proportion as the total resistance is greater; it is on this account that Fechner has been able to obtain very exact results by the application of the third method, even in the case of currents of non-constant force. M. Poggendorff has moreover proposed for the determination of the electro-motive force of these currents, a much more exact method, which is founded upon a rigorous principle. It rests upon the theory of compound circuits; that is, circuits formed by the union of two or more pairs, in which we admit, as follows from the experiments of Fechner, Pouillet, and Poggendorff himself, and, as we have reported above, that

* Vol. I. p. 216.

the electro-motive force of a compound circuit is the sum or the difference of the electro-motive forces of the simple circuits, of which it is composed, and that its resistance is, in like manner, the sum of the resistances of the simple circuits. M. Poggendorff's method requires the employment of a pair of constant force, such as a Grove's pair, the electro-motive force of which has been determined by one of the three preceding processes, which are applicable in this case; and we compensate, by means of the current of the pair, that of the pair of non-constant force, whose electro-motive force we desire to determine; on this account it is, that this method has received from its author the name of *compensation method.* In the application of his method M. Poggendorff employs two processes, the second of which has the advantage over the first of not requiring a perfect and very prolonged constancy, of the pair with constant force,—a condition generally difficult of realisation,—and of not imposing the necessity of knowing beforehand the two elements e and r, of this pair.* However, as it is nevertheless of importance, even in the employment of the second process, to know how to determine the electro-motive force of a pair with constant force; and since moreover this determination is at once the most simple and the most important in practice, it is by this that we shall commence, making use for this purpose of a fifth method, which is that of Wheatstone.

Mr. Wheatstone first remarks, that if in a circuit the electro-motive force and the resistance are increased in the same ratio, the intensity of the current does not change; thus $i = \frac{e}{r} = \frac{ne}{nr}$. It follows from this, that a single voltaic pair, or a pair composed of any number of similar pairs ought to give rise to currents of the same intensity, provided that each pair is introduced with its own resistance, without interposing any additional resistance. Every new resistance interposed diminishes the force of the current, but its effect is in proportion less, as it is smaller in respect to the total

* See, for the details of Poggendorff's method, the final Note F., which is devoted to the more mathematical explanation of the different methods.

resistance of the circuit; whence it follows that if, into two circuits, which produce currents of equal force, but in which the resistances and consequently the electro-motive forces are very different, the same resistance is introduced, the intensities of the two currents will be weakened in very different proportions also. This is why the same resistance, — that arising, for example, from the introduction of a voltameter, weakens in a much more considerable proportion the intensity $i = \frac{e}{r}$ of the current arising from a single pair, than the intensity $i = \frac{n\,e}{n\,r}$ arising from the current of a circuit of n pairs, placed in series. These principles, which flow from what we have already said above, and in particular in the First Chapter of our Fourth Part*, explain why it is necessary to employ a series of pairs, in proportion more numerous as the resistance, that the current encounters, is more considerable.

After having related the principles, which precede, let us see the application, that Wheatstone has made of them. In order to avoid having to measure the variable intensities of the currents, either by sine or by tangent galvanometers, or by the number of oscillations of a magnetised needle, measures scarcely susceptible of a rigorous accuracy, he introduces into the circuit, instead of constant resistances, variable resistances, thus bringing back to equality the currents produced in the circuits, whose electro-motive force is compared; he then concludes from the total of the additional resistance, introduced in each case, in order to pass from a certain deviation, always the same, of the needle of the galvanometer, 45° for example, to another deviation of 40°, always the same also, the relative values of the electro-motive forces, and of the resistances of the circuit, according to the particular conditions of the experiment. It is by no means necessary, in this method, to know the forces corresponding to the deviation of the needle.

Mr. Wheatstone, in order to introduce into the circuit a

* Vol. II. pp. 77. and following pages.

variable resistance, employs the rheostat of which we have already given a detailed description.* The copper wire of the instrument being interposed in the circuit, we have merely to elongate or to shorten it by a quantity, that may be measured with the greatest accuracy, in order to add to or to withdraw a resistance, which is expressed in lengths of this wire. When the object is to measure resistances too great for the introduction of the entire wire of the rheostat, although it may be very long, to be able to bring back the current, so as to deviate the needle of the galvanometer no more than the desired quantity of 45° for example, resistance bobbins are introduced into the circuit, which are arranged beside the rheostat, as is indicated in the figure, so that we are able to interpose a greater or less number of them. We thus succeed in reducing the current to the intensity of 45°, by completing, by means of the rheostat, what is wanting to the added resistance, in order to attain exactly to this deviation,— a resistance, moreover, which it is not necessary to know, since the object we have to measure is simply the length of the wire of the rheostat, which is necessary to be added, in order that the current may pass in each case from the intensity of 45° to that of 40°.

Now, let $i = \frac{e}{r}$, i having been brought to produce 45° on

* Vol. II. p. 88. (*fig.* 181.) ; we reproduce the figure here.

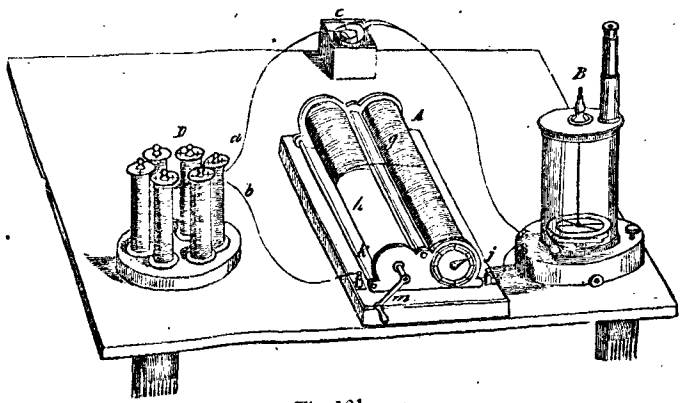


Fig. 181.

the galvanometer with the pair whose electro-motive force is e, and its resistance r; let l be the reduced length of the wire of the rheostat that it is necessary to add to r, in order that i shall become i', and not produce more than 40° on the galvanometer. We have $i' = \frac{e}{r + l}$; let there now be another voltaic combination, the electro-motive force of which is $e' = n\,e$. In order that its current may have only the intensity i, producing 45°, it is necessary that the resistance be $r' = n\,r$, which will be obtained by means of the resistance bobbins; we shall have, in fact, i or $\frac{e}{r} = \frac{n\,e}{n\,r}$; but, in order to bring back i to be no more than i', namely 40°, it is necessary that the additional resistance, or the added length of the wire of the rheostat, be $l' = n\,l$; for since we have $i = \frac{n\,e}{n\,r}$, in order to obtain $\frac{n\,e}{n\,r + l'} = i'$ or $= \frac{e'}{r + l}$, it is evidently necessary that l' be equal to $n\,l$. Now, n is the relation of the two electro-motive forces e and e'; we see that it is the same as that of the two quantities l and l', with which it is necessary to elongate the wire of the rheostat, in order to cause the currents of the two pairs, whose electro-motive forces are e and e', to pass from 45° to 40°; its determination is therefore very easy. In the application that we are about to make of this process to the determination of the electro-motive forces of the different voltaic combinations, we shall content ourselves, in order to express the added lengths of the wire of the rheostat, to indicate the number of turns which this wire has been unrolled, each turn corresponding to a length of 3·46 inches.

Three pairs, differing only by their dimensions, each composed of a liquid amalgam of zinc placed in a cylindrical porous cell, which is plunged into a vessel, filled with a solution of sulphate of copper, in which is also immersed a hollow copper cylinder, were successively placed in a circuit, of which the rheostat formed part. All three equally required thirty turns of the rheostat, in order that their

current might be brought from 45° to 40°. One however was 2 in. high, and $1\frac{1}{2}$ in. in diameter; the second $3\frac{1}{2}$ in. high, and $2\frac{1}{2}$ in. in diameter; the third 6 in. high, and $2\frac{1}{2}$ in. in diameter. Thus the electro-motive force is entirely independent of the size of the surfaces of the pairs: this is a consequence of the nature of this force, as we have already remarked.

It is not the same with the influence of the number of pairs. It is easy to prove that the electro-motive force increases proportionably to this number, conformably to theory. Thus, with a circuit formed successively of 1, 2, 3, 4, and 5 similar pairs of the smallest of those which we have just now employed, we find that, in order to bring the current from 45° to 40°, it requires,—

With 1 pair	- -	30 turns.
2 „	- -	61 „
3 „	- -	91 „
4 „	- -	120 „
5 „	- -	150 „

We see therefore that, except for the case of two and of three pairs, in which there is a slight difference, arising from a small error of experiment, the law is verified exactly.

If we now pass to the determination of the electro-motive force of pairs of different kinds, we find first a very remarkable result; it is that, when we confine ourselves to changing in the pair, — amalgam of zinc, sulphate of copper, and copper, — the sulphate, providing it is still a salt of copper, substituting for it the acetate, the protochloride, the nitrate, or the ammoniacal sulphate, we obtain the same electro-motive forces, except as far as concerns the nitrate, which gives a variable result, probably on account of the action of the nitric acid upon the mercury. Another curious fact is, that neither does the proportion of zinc in the liquid amalgam appear to affect the electro-motive force of the pair, only the action does not last so long a time. In fine, it is a result altogether similar to that which has shown us, that the influence upon the electro-motive force of the extent of the surface of contact between the metals of the pair and the liquid with which it is charged,

is altogether null. The quantity of zinc dissolved in the amalgam determines the number of points of the surface of this amalgam, susceptible of being attacked by the liquid; it produces, therefore, in varying, the same effect as an increase or a diminution in the surface of the same amalgam, that is to say, a null effect upon the electro-motive force; the latter being in fact only the property possessed by the current of surmounting a given resistance, it must be the same for each point of each molecule of the surface attacked; with regard to the absolute quantity of electricity that passes, it is clear that it varies with the number of points attacked; but it is not this that we are measuring here.

The greatest electro-motive force that can be possessed by a voltaic pair, composed of two metals and one interposed liquid, is obtained when the liquid is a solution of a salt, having the negative metal for a base. In fact, in this manner we avoid the deposit upon this metal of heterogeneous matters, which, by polarising it, notably reduce the electro-motive force. Thus, on substituting in the pair, — amalgam of zinc, sulphate of copper and copper,— diluted sulphuric acid for the sulphate, we obtain only twenty turns of the rheostat, instead of thirty, for the expression of the electro-motive force. In like manner, if we substitute in a pair,— amalgamated zinc, chloride of platinum, platinum,— diluted sulphuric acid for the chloride, we obtain no more than twenty-seven turns, instead of forty. The following is, moreover, a Table of the electro-motive forces of different pairs: —

			Turns.
Amalgam of Zinc - -	diluted sulphuric acid -	copper - - -	20
"	" -	platinum - -	27
"	sulphate of copper - -	copper - - -	30
"	chloride of platinum -	platinum - -	40
"	diluted sulphuric acid -	peroxide of manganese	54
"	" -	peroxide of lead -	68
Potassium -	sulphate of zinc - -	zinc - - -	29
"	sulphate of copper - -	copper - - -	59
"	chloride of platinum -	platinum - -	69
"	diluted sulphuric acid -	peroxide of manganese	84
"	" -	peroxide of lead -	98

An important point, for the theory of the pile, which Mr. Wheatstone has been able to verify by means of his method, is that, if we take three metals, in their electro-motive order, the electro-motive force of a pair formed of the two extreme metals is equivalent to the sum of the electro-motive forces of the two pairs, formed of the consecutive metals. Thus, with —

Amalgam of potassium, sulphate of zinc, amalgam of zinc,		29 turns.
„ zinc, sulphate of copper, copper - -	30	„
„ potassium, „ „ - -	59	„
Amalgam of potassium, sulphate of zinc, amalgam of zinc,		29 turns.
„ zinc, chloride of platinum, platinum - -	40	„
„ potassium, „ „ - -	69	„

In both examples the electro-motive force, deduced from reasoning, is found to be exactly equivalent to that furnished by experiment.

We may remark, in passing, the great electro-motive force of potassium, as well as that of sodium, which is scarcely less, which is due to their powerful affinity for oxygen, and to the facility with which consequently they decompose water.*

A sixth method, under the name of *method of opposition*, has been proposed by M. Jules Regnault, for the determination of electro-motive forces; it has been likewise employed by Gaugain. It is based upon this principle, demonstrated by experiment, that if two pairs composed of the same solid and liquid elements are opposed to each other, that is to say, so arranged that, when they form a circuit, the positive element

* M. Goodman has found, that the most convenient manner of employing potassium in the formation of a voltaic pair, consists in placing it at the bottom of a tube, closed by a membrane, and to place this membrane in contact by its lower part, with the surface of the acidulated water, which covers a horizontal plate of platinum. A drop of mercury, placed upon the membrane, serves to retain the surface of potassium, exposed to the action of the acidulated water, always amalgamated; and oil of naphtha, with which the tube is filled, preserves it in all the rest of its surface from the oxidising action of the air. A copper wire, planted in the piece of potassium, permits of closing the circuit. If a solution of sulphate of copper, is substituted for that of sulphuric acid, the current is more constant, but more feeble. A pair thus constructed, powerfully decomposes acidulated water, placed in a voltameter with platinum wires; 12 ranged in series gives almost as much tension as Gassiot's 3520 water pairs, and Grove's 100, provided they are well insulated; a single one produces a slight divergence of the gold leaves of the electroscope. According to Henrici, the amalgam of sodium has an electro-motive force, almost as great as that of potassium.

of the first is joined to the positive element of the second, and their two negative elements communicate in like manner, there is not the least current in the system. But, if the two pairs differ, there is a circulation of a current in the circuit: and the direction of this current is determined by that of the current, which arises from the pair, whose electro-motive force is greater. Mr. Faraday, in his researches on the chemical origin of voltaic electricity, quotes a great number of experiments, by which this principle is established. The most natural manner of interpreting it is to admit that, in the former case, equilibrium arises from the circumstance that the opposed electro-motive forces are equal; then in fact, the tendency to polarisation of all the parts of the circuit, as well solid as liquid, being exerted with exactly the same power, but in two opposite directions, its effect must be null. It is as if the two pairs of *fig.* 307. p. 688. were so arranged, that the zinc of the first communicated with the zinc and not with the platinum of the second, their electro-motive force, instead of becoming double, would become null. *In the latter case, the electro-motive force being unequal, the intensity of the current must be proportional to the difference of the electro-motive force of the two pairs.* With regard to the resistances that the current must surmount, they are the same, in whatever manner the pairs are arranged, so that we have $i = \frac{e-e'}{r+r'}$, $\frac{e}{r}$ and $\frac{e'}{r'}$ being the respective intensities of the two pairs that are opposed. If the opposition of the two pairs annihilates the current, that is to say, renders i equal to 0, we must necessarily conclude from it that $e' = e$.

The same reasoning applies to the pairs in series, that constitute piles. Thus we obtain $\mathrm{I} = \frac{n\,e - n'\,e'}{\mathrm{R}+\mathrm{R}'}$, n being the number of pairs of the first pile, e the electro-motive force of each of them and R the sum of their resistances, n' and e' and R′ being the corresponding values for the second pile. If I is null, we have $n\,e = n'\,e'$; and if e' is made $= 1$, namely, if we take for unity the electro-motive force of the more feeble pair, we obtain, supposing also $n = 1$, $e = n'$, that is to say, that

the electro-motive force of the stronger pair is equal to n' times the electro-motive force that has been taken for unity; n' being the number of the more feeble pairs, which make equilibrium with the single stronger pair.* The reasoning, that we have just made, is based upon the principle, that we have demonstrated by experiment, namely, that the electro-motive force is proportional in a circuit, composed of many pairs, to the number of these pairs arranged in series. It is equally accurate, whether currents do not circulate, when the electro-motive forces are equal, or whether they circulate simultaneously, but in a contrary direction, so as to annihilate each other in their common circuit, as we have supposed in the First Section of this Chapter; a supposition, moreover, that the analysis of the phenomena had led us to abandon, in order to admit that, which we have just now pronounced for the first time.

Before speaking of the applications that M. J. Regnault has made of his method to the determination of the electro-motive force of some voltaic combinations, it is important to fix for a moment our attention upon a point, with which we have not yet been occupied, it is the choice of a unit, to which the various electro-motive forces may be referred, or with which they may be compared. This unit must be an electro-motive force. M. J. Regnault takes for this unit the electro-motive force of a thermo-electric pair,— bismuth and copper, — for a difference of 32° and 212° between the solderings. Then, making use of a thermo-electric series composed of sixty similar pairs, taking care that the solderings of the even and of the odd rank remain at temperatures sensibly fixed during the continuance of the experiments, he seeks to know how many of these pairs must be employed in order to produce equilibrium to a pair, whose electro-motive force we desire to determine. It is thus, that the current of a pair, — zinc in sulphate of zinc, and cadmium in sulphate of cadmium, — is found to be counterbalanced by the thermo-elec-

* It seems to us, that it may frequently happen that n is not equal to 1, although less than n'; then, when we have found the number of pairs of each species, that must be placed in series, in order that their opposition may produce equilibrium, we have $n\,e = n'$, whence $e = \frac{n'}{n}$.

tric current of fifty-five pairs, — bismuth and copper, — the solderings of which present differences of 32° to 212°. But this pair being one of those, whose electro-motive force is the most feeble, it would be necessary to multiply for others in an enormous proportion the number of thermo-electric pairs. Thus, M. J. Regnault proposes to take, for an auxiliary pair, that of zinc-cadmium, the two metals plunging in their respective sulphates, which is endowed with a remarkable constancy; it is with this that the others are compared, remembering that its electro-motive force is equal to fifty-five times that, which is taken for the unit.

Mr. Wheatstone had likewise determined, by his method, the relation that exists between the electro-motive force of a thermo-electric pair, — bismuth and copper, — the solderings of which were respectively at the temperatures of 32° and 212°, and that of the pair, — amalgam of zinc, sulphate of copper and copper; and he had found that, whilst it required for bringing back the deviation of the needle with the former from 10 to 5° *, only eight times of the rheostat, it required 757 with the latter; which established between the two electro-motive forces the relation of 1 to 94·6. M. Pouillet, by an entirely different method, of which we shall speak presently, had found the relation 1 to 94. M. J. Regnault has found a very different relation; namely, that of 1 to 153; which he attributes to the circumstance, that in Mr. Wheatstone's pair a difference in the nature of the porous diaphragm, which it is difficult to have indentical, may considerably modify the electro-motive force, as has been demonstrated to him by the experimental comparison that he has made between a Daniell's pair, the diaphragm of which was of unglazed porcelain, and a Wheatstone's pair, with diaphragms of different natures.† Moreover, this influence of the nature

* The thermo-electric current was too feeble to cause the needle of the galvanometer to deviate from 45° to 40°, as in the preceding experiments; it was necessary, in the comparison of this current with that of the hydro-electric current, to have recourse to the deviation from 10° to 5° only.

† The difference of the two electro-motive forces was deduced from the opposition of the two pairs; it was found 3 units in favour of the Daniell's pair, when the two pairs had each a diaphragm of unglazed porcelain; but it was successively 26, 44, and 103 in favour of the Wheatstone pair, when the diaphragm of this latter were pipe-clay, bladder, beech.

of the porous diaphragm upon the electro-motive force is no longer sensible in the piles of two liquids, as M. J. Regnault has further proved with two different pairs, the one zinc-cadmium, with sulphate of zinc and sulphate of cadmium; the other Daniell's zinc-copper, with sulphate of zinc and sulphate of copper; he always found that the electro-motive force of the former was equal to 55 times that of the thermo-electric pair, taken for unity, and that of the latter to 175 times this unit, whatever diaphragm was employed in the two pairs,— unglazed porcelain, pipe-clay, bladders, and different species of wood.

With regard to the unit chosen by M. Regnault, which is the same as M. Pouillet has also adapted, it appears to me to present two inconveniences; the first, of being unable to be found always exactly the same*; the other, of being led into an electro-motive force of an entirely different species, in regard to its intensity and its origin, from that of hydro-electric pairs. It would seem to us that it would be preferable to adopt for these latter a unit, taken among the electro-motive forces of hydro-electric pairs, chosing one of those, which would give the most constant current. Moreover, M. J. Regnault has plainly seen this, for it is finally to the electro-motive force of the pair,— zinc-cadmium, sulphate of zinc, and sulphate of cadmium,—that he has compared that of divers hydro-electric pairs.

M. J. Regnault has confirmed, for potassium and for zinc, by making use of his method, the fact pointed out by Mr. Wheatstone, that the proportion of positive metal, contained in the liquid amalgam, does not appear to affect the electro-motive force of a voltaic pair of which it forms part. Thus, he has found the electro-motive force of a pair,— amalgam of zinc-copper, charged with sulphate of zinc and sulphate of copper, equal to 178 of these units, whether there was $\frac{1}{20}$, $\frac{1}{200}$, or $\frac{1}{400}$ of zinc dissolved in the mercury. In like manner he has found this force equal to 416, whether there was

* M. J. Regnault has recognised this inconvenience; thus, he has been occupied in searching for the means of giving to the current produced, by a greater or less number of consecutive thermo-electric pairs, the greatest possible constancy; but we are not satisfied that he has succeeded.

$\frac{1}{130}$ or $\frac{1}{1500}$ of potassium dissolved in the mercury with a pair,— liquid amalgam of potassium and platinum, charged with chloride of sodium and chloride of platinum. The result is, within certain limits, the same, as far as the degree of the solution in which the positive metal is plunged, is concerned. M. Regnault has found that this degree may vary from 1 to $\frac{1}{100}$, without the electro-motive force of the voltaic combination being sensibly disturbed. We must not lose sight, in this case, as in that of the amalgam of zinc, that the question here is not of the quantity of electricity produced in a given time, but of the faculty of this electricity of surmounting a certain resistance.

M. J. Regnault, who, like Mr. Wheatstone, has applied his method to the determination of the electro-motive forces of certain voltaic combinations, has found in general, in the small number of cases that he has studied, that the electro-motive force does not very sensibly change in a pair of two metals, which plunge each into a saline solution, with the nature of this solution, provided that it has for a base the same metal, that is immersed in it. However, there are many exceptions to this law, which would seem to be tolerably true only when the metals, which form the pairs, are very far from each other in the electro-motive series, such as zinc and copper, or zinc and platinum.

We have seen above, that M. Poggendorff had proposed a method, in regard to the case of pairs of non-constant force, in order to be able to escape the influence of the polarisation of the negative metal, which occasions so prompt an alteration in the electro-motive force of these pairs. But a great number of philosophers have sought to appreciate this influence directly, by determining the electro-motive force of the pairs, formed by polarised metals, that is to say, by metals, whose surface is covered with those thin deposits, which imparts to them secondary polarity.

Wheatstone, in his work upon electro-motive forces, had made an important remark upon this subject, namely, that the electro-motive force, contrary to that of a voltaic circuit, which arises from the interposition in this circuit of a voltameter with platinum electrodes, charged with a solution of

sulphuric acid, is constant; that is to say, is the same, whatever be the force of the current. In order to obtain this result, Wheatstone placed the same voltameter successively in four circuits, composed of 3, of 4, of 5, and of 6 of his pairs; and he determined in each the electro-motive force *without* and *with* the voltameter; then, deducting the number of turns, which expressed the latter, from that which expressed the former, he obtained a difference always the same, which was the expression of the contrary electro-motive force exerted by the electrodes of the voltameter. The following is the Table of the experiments: —

No.	Without Voltameter.	With Voltameter.	Difference, or Electro-motive Force of the Voltameter.
3 pairs.	90	21	69
4 „	120	50	70
5 „	150	79	71
6 „	180	109	71
		Mean	70

Thus, the electro-motive force, due to the polarisation of the platinum electrodes of the voltameter, may be regarded sensibly as constant and equal to 70, which causes it to be, to that of a single pair, as 70 is to 30, or as 7 is to 3; and which establishes between these two forces the relation of 2·33 to 1. On this account it is that at least 3 pairs, constituting a voltaic combination of an electro-motive force of 90, are necessary, in order to decompose water with the voltameter.

M. Svanberg, after having found with a Daniell's pile almost the same relation, namely, that of 2·20, in place of 2·33, between the electro-motive force of the polarised electrodes P, and that of a pair E, satisfied himself that there is polarisation only on the surface upon which the gas is liberated. He operated, as Wheatstone had done, with a rheostat. He first placed in the circuit of three Daniell's pairs, instead of the voltameter, a copper-platinum pair, the copper plunging in a solution of sulphate of copper,

and the platinum in a solution of sulphuric acid; the latter serving as positive electrode. By supposing that this alone is polarised, and calling this force of polarisation p, and the electro-motive force of the pair itself, copper-platinum e, which acts in a contrary direction to that of the pile, E being that of one of the Daniell's pairs, we have,

$$3\,\mathrm{E} - e - p = 18{\cdot}01.$$

If now we introduce into the circuit of four Daniell's pairs the copper-platinum pair, so that the copper is positive electrode, and the platinum negative, receiving the hydrogen, we find, by experiment, on remarking that in this case the electro-motive force of the copper-platinum pair must be added, instead of being deducted, and calling the force of polarisation of the negative platinum p',

$$4\,\mathrm{E} + e - p' = 50{\cdot}03.$$

But $3\,\mathrm{E} = 42{\cdot}79$ by experiment; whence $\mathrm{E} = 14{\cdot}26$; and consequently $4\,\mathrm{E} = 57{\cdot}05$; which gives,

$$\begin{array}{rl} & p + e = 24{\cdot}78 \\ & p' - e = \ 7{\cdot}02 \\ \text{whence} & p + p' = 31{\cdot}80 \end{array}$$

$$\text{and} \quad \frac{p + p'}{\mathrm{E}} = 2{\cdot}16.$$

But we had found $\frac{\mathrm{P}}{\mathrm{E}} = 2{\cdot}20$; therefore we have $p + p' = \mathrm{P}$.

The result shows us, therefore, that there is no polarisation except on the electrode, where the gas is liberated; that, consequently, in the former case, there is none upon the copper; which, serving as negative electrode in sulphate of copper, simply covers itself with revived copper; and that neither is there any in the latter case, in which the copper, serving as positive electrode in diluted sulphuric acid, oxidises and dissolves. The platinum plate is therefore the only one polarised in the two cases; in the former, by the oxygen, which gives to it a force of polarisation $p = 20{\cdot}03$, and in

the latter by the hydrogen, which gives to it a force $p' = 11{\cdot}77$.*

M. Svanberg has endeavoured to determine the force of polarisation of hydrogen, when it is liberated upon copper; but he has found that it was very variable with the degree of polish of the surface of the metal. Thus it was only 1·96 when the surface of the copper was granulous, and 12 when this surface was perfectly polished, that is to say, equal to the polarising force of hydrogen upon a polished surface of platinum.

MM. Lenz and Saweljev, in a considerable work upon the electro-motive force, developed by the polarisation of the plates of the electrodes, have generalised Svanberg's result, and they have arrived at the following laws: — 1st. The polarisation of the plates, that are employed as electrodes, takes place only so long as gases are liberated upon their surface. 2nd. The polarisation that results from the decomposition of a liquid between two electrodes is the sum of the polarisation produced upon each electrode. 3rd. The polarisation and the electro-motive forces, in each cell of the circuit, where decomposition takes place, are summed up, algebraically speaking, that is to say, each with its sign depending upon the direction, in which it acts. 4th. We may range in order all the various combinations of a metal with a liquid, under the relation of their electro-motive forces, in a series, in which each is positive in respect to that which precedes; and the resulting electro-motive forces being able to be expressed by numbers, such that those, which would result from the reunion of any two combinations, are represented by the difference of the two corresponding numbers. 5th. To the experimental demonstration of these four laws are attached two Tables, one of which gives the values of the secondary polarities of certain metals in oxygen and in hydrogen, and the other that of the electro-motive forces of different metals in their contact with different liquids, eliminating the contrary element of polarisation. In these two Tables the unit is altogether arbitrary; since

* One would be surprised to see the polarising force of oxygen superior to that of hydrogen, contrary to what Grove had found with his gas pile; but it is necessary to remark, that here the oxygen arises from the decomposition of water, and that it is ozonised.

it depends upon the particular instrument, that has been employed in the determinations; but as it is a question of relations only, it possesses no inconvenience.*

FIRST TABLE.

	Polarisation.	In Units of the Rheostat.
Platinum in oxygen	2·49	48·8
„ chlorine	0·00	00·0
Graphite in oxygen	1·33	26·0
Gold „	2·71	51·1
Platinum in hydrogen	3·67	71·9
Zinc „	0·90	17·6
Copper „	2·30	45·0
Tin „	1·55	30·4
Iron „	0·48	9·4
Mercury „	4·37	85·6
Copper in oxygen	0·69	13·5

SECOND TABLE.

	Electro-motive Forces.	In Units of the Rheostat.
Platinum in hydrochloric acid	0·26	5·1
„ sulphuric acid	0·02	0·4
„ acetic acid	0·00	0·0
Graphite in nitric acid	0·01	0·2
Gold „ „	0·06	1·2
Gold in sulphuric acid	0·25	4·9
Mercury „ „	0·70	13·7
„ acetate of protoxide of copper	0·79	15·5
Platinum in a solution of potash	1·20	23·5
Pure copper in sulphuric acid	1·39	27·2
Slightly oxidised „ „	1·75	34·3
Copper in sulphate of copper	2·00	39·2
Gold in a solution of potash	2·31	45·2
Tin in hydrochloric acid	2·38	46·4
Iron „ „	2·75	53·9
Graphite in potash	2·84	55·0
Iron in sulphuric acid	2·92	57·2
Tin „	2·95	57·8
Copper in a solution of potash	3·10	60·7
Tin „ „ „	3·94	77·2
Zinc in diluted nitric acid	4·01	79·2
„ „ hydrochloric acid	4·07	79·9
„ „ sulphuric acid	4·17	81·9
Iron in a solution of potash	4·65	91·1
Zinc „ „	5·48	107·4

* The unit of the current was, that which deviated the needle of the galvanometer 1°; the unit of resistance, that of 1 turn of the rheostat; the unit of electro-motive force, that which produced with the resistance 1, the current 1.

The method employed by MM. Lenz and Saweljev consisted in having two liquids, separated by a porous diaphragm, into each of which was plunged a metal plate, serving as an electrode; a multiplier and a rheostat, or agometer, as these philosophers call it, being with the decomposition cell introduced into the circuit of a Daniell's pile. The needle of the galvanometer was brought, by means of the rheostat, first to a certain degree of deviation, then to another; then the same operation was performed, simply removing the decomposition cell from the circuit; the whole repeated several times, in order to obtain exact means; and, from the comparison of the results, the contrary electromotive force exerted by the decomposition cell was deduced, and consequently the polarisation of its plates. It is thus, as we are about to see, that the Tables above have been drawn out.

Admitting that the polarisation is produced simply by the liberation of the gas, in order to determine the polarisation of each electrode in particular, in the case of the decomposition of water by platinum electrodes, we begin by determining it in the case, in which the two platinum plates are plunged into nitric acid; because there is then no liberation of hydrogen at the negative electrode: we obtain the value of the polarisation, due to the oxygen, which is found equal to 2·48; then, going through the same operation by plunging the platinum plates into diluted sulphuric acid, we obtain a polarisation, equal to 5·46, which is the sum of the polarisations, due respectively to the oxygen and the hydrogen, since there is a liberation of gas upon both the electrodes. In order to obtain the latter, that due to the hydrogen, we have only to deduct 2·65 from 5·46, which gives 3 for its value. But this value changes with the metals, upon which the hydrogen is deposited. Thus, with amalgamated zinc, it is only 1·00; with copper, 2·15; with tin, 1·45; with iron, 0·33, &c. These numbers differ but little from those of the Table, which are more exact, seeing that they have been obtained at the end of more numerous and more varied experiments.

With regard to the Table of the electro-motive forces of

metals in various liquids without polarisation taking place, it has been likewise drawn out, either by means of direct observations or by deducting from the observations, in which polarisation intervenes, the effect due to this polarisation, which had been determined directly.

M. Beetz, who has also been occupied with the electromotive force of gases, has employed a method altogether different from, and much more direct than that of MM. Lenz and Saweljev; he has applied quite simply Poggendorff's process of compensation to Grove's gas pile, charging it successively with various gaseous substances, and employing a zinc-platinum pair of Grove's in order to establish compensation. He took great precaution in the preparation of the platinums, of the gas pile and of this pile in general, in which he took care to introduce only very pure gases, after having driven out all the air from the solution of sulphuric acid, with which the tubes were filled, that were about to receive the gaseous substances. The following is the Table of the electro-motive forces developed by associating with hydrogen, which was always in one of the tubes, the various substances the names of which follow, and among which M. Beetz introduced two solids, namely, platinum without gas in immediate contact with the liquid, and platinum covered with copper; it is very remarkable, that the order, in which the various substances are ranged, with regard to their electromotive force, is exactly the same as that which Grove had found.

Names of the Substances.	Electro-motive Forces.
Chlorine	31·49
Bromine	27·97
Oxygen	23·98
Oxide of nitrogen	21·33
Cyanogen	21·16
Carbonic acid	20·97
Oxide of nitrogen	20·52
Iron	20·50
Platinum	20·13
Sulphuret of carbon	19·60
Olefiant gas	18·36

Names of the Substances.	Electro-motive Forces.
Phosphorus	16·06
Oxide of carbon	13·02
Copper	3·82
Sulphuretted hydrogen	3·05
Hydrogen	0·00

Beetz's experiments have shown that, conformably to Mr. Grove's opinion, oxygen contributes in a direct manner to the development of the current in the oxygen-hydrogen pile; since, when hydrogen is associated with oxygen, the electro-motive force is 23·98, whilst it is no more than 20·13, when it is united with platinum, which gives 3·85 for the electro-motive force of platinum covered with oxygen. This is not an effect due to the depolarising action of oxygen, since the circuit remains closed for an instant only. It is to the former cause that must be attributed the fact, likewise observed by M. Beetz, and already pointed out, as we have seen, by M. Poggendorff, that platinum plates, provided they are well cleaned, give as much effect as when they are platinised, which is due to their not having time to become polarised; now, it is their faculty of polarising much more powerfully than platinised plates, which gives to them a great inferiority when the circuit remains for a long time closed.

The influence, that is exerted in general over the phenomena of this order by the nature of the solid substance, upon the surface of which the gaseous film is found, arises from the fact that this surface is never entirely covered by the gas, and that there are always some points of contact between it and the liquid. If the immersed plates could be entirely insulated from the liquid by the gases, with which they are enveloped, the chemical nature of the metallic masses would be altogether indifferent. When the plates are covered with gas by means of electrolytic decomposition, they are so in a much more complete manner than by any other means; but they are never sufficiently so, even when the maximum of polarisation has been imparted to them, for the nature of the metal to play no part. However, the electro-motive power developed by this means, instead of being 24, as M. Beetz had found it, by means of oxygen and hydrogen

introduced into the tubes, is, according to M. Poggendorff, 55 when the platinum plates possess their metallic brilliancy, and 40 when they are platinised. Still recognising that the oxygen and hydrogen, which arrive on the surface of the platinum by the electrolytic way, form upon it much more continuous deposits, we believe that this enormous difference is due especially to the fact, that the oxygen, when it is produced in this manner, is ozonised; a circumstance, that considerably augments its electro-motive force, as we have seen it do.

There is a point upon which M. Beetz does not agree with MM. Lenz and Saweljev; it is that which concerns the electro-motive force of chlorine which these philosophers had found to be null, which is probably due to the fact that the platinum, in their experiments, was attacked by the chlorine, and formed a chloride, which was dissolved. M. Beetz, in numerous and laborious researches, which we regret being unable to report here a little more in detail, has constantly found, both in operating directly upon gaseous chlorine, as well as in depositing chlorine upon platinum by the electrolytic decomposition of the chlorides, or of hydrochloric acid, numbers very near to each other, 10·27 and 11·0, for the force of polarisation of *platinum-chlorine;* he has likewise found, for that of *platinum-hydrogen*, 19·08; which, added to the former, produces about 30; a number a little lower only than that, furnished by direct observation, made with the gas pile,—hydrogen and chlorine. On decomposing iodides and bromides, M. Beetz was able likewise to determine the electro-motive force of iodine and bromine, which he found to be for the former, 3·36, the latter 6·96, that of chlorine being 10·10.

It evidently follows from the analysis, that we have just been making of the works, relative to the electro-motive force of gases, that the numerical determinations leave still some uncertainty in respect to the influence that is exerted upon the force of the current by the nature of the solid substance, that establishes contact between the gas and the liquid, and by the manner, in which the deposit has been brought about.

A point upon which philosophers are not in accordance, is the relation, that exists between the secondary polarities, acquired by the plates, that have been employed as electrodes to a current in an electrolytic liquid, and the intensity of this current. We have seen that, according to Wheatstone, the energy of the secondary polarities would be constant and independent of the intensity of the current. M. Poggendorff has arrived at a different result, and he has found that this energy increases with the intensity of the current, and in a the manner more sensible in proportion as the latter has a less absolute force. He operates with a pile of two Grove's pairs, the electro-motive power of which he first determines when it is alone, then when a voltameter is introduced in it, that is an inactive pair of two platinum plates, plunged in diluted sulphuric acid. Then, causing the length of the wire of the rheostat, which is placed in the circuit, to vary, he notices what are the corresponding variations that are suffered by the electro-motive force of the new circuit, which is equal to the difference between the primitive electro-motive force of the two Grove's pairs, and the contrary one, that results from the secondary polarities acquired by the two plates of platinum. Now, if this latter is constant, the former being evidently so, their difference ought to be so also, which is not the case, as is proved by the following Table, in which l expresses the length of the wire of the rheostat, i the intensity of the current, measured by the sine-galvanometer, E' the electro-motive force of the circuit, and p, the electro-motive force, arising from the secondary polarities acquired by the plates; p is obtained by deducting E' from E, the electro-motive force of the circuit, before the introduction of the inactive pair of platinum, which is found equal to 46·85, on commencing the experiments, and to 46·53, on finishing, which proves the constancy of the pile. With regard to the total resistance of the circuit, including the wire of the sine-galvanometer, it was 8·78 before the introduction of the inactive pair, and 12·79 when once the pair is introduced.

l.	i.	E'.*	p.
6	80·15	18·51	28·18
8	62·58		
10	54·17	18·50	28·19
20	34·56	18·77	27·92
40	21·17	19·16	27·53
80	12·14	19·66	27·03
160	6·42	20·16	26·53
340·87	3·27	21·28	25·41
80	12·80	19·50	27·19
40	21·11	19·08	27·61
20	34·12	18·43	28·26
10	53·39	18·36	28·33
8	61·27	18·26	28·43
6	76·41	18·28	28·41

We may remark however, that the differences observed by M. Poggendorff between the different values of p, are not very great, and may be due to the inconstancy, that is always more or less presented by the secondary polarity of the positive electrode, on account of the presence at this electrode of a greater or less proportion of ozonised oxygen.

M. Poggendorff has applied the determination of secondary polarities to the evaluation of the total resistance that is exercised upon a current by the current, produced by a more feeble pair, placed in the circuit of the stronger, but in a contrary direction. He has thus found that a simple pair, zinc-platinum, or zinc-copper, in a solution of sulphuric acid, interposed in this manner in the circuit of a pile of three pairs of Grove's, so that the hydrogen is deposited upon the zinc and the oxygen upon the platinum or the copper, exercised a force of resistance, which was exactly the sum of its electro-motive force proper, and that arising from the secondary polarities of the two plates.

The principle thus enables us to estimate the electro-motive forces of pairs of non-constant force, when once we

* The first value of E' was deduced from the two intensities, 80·15 and 62·58, by means of Ohm's method, which was allowable, in consideration of the small interval of time, that had elapsed between the two consecutive experiments.

know the electro-motive forces developed by the secondary polarities, that it is necessary, in this case, to deduct from those which are furnished by experiment, in order to obtain the electro-motive force of the pairs themselves, before their plates have been polarised. It is by this means that MM. Lenz and Saweljev had drawn out the Second Table, that we have reported above, and which contains the electro-motive forces of the metals, plunged in divers liquids. M. Poggendorff remarks moreover with reason that, for the determination of the electro-motive forces of the pairs of non-constant force, his method of compensation has the advantage of being more direct and more exact.

This method of M. Poggendorff's, which we have merely pointed out, and which we have developed in the Note F, has enabled its author to throw light upon many points that are still obscure, relative to the influence of certain causes on the electro-motive force. Thus we had observed that, when the resistance is not very great, the current of a zinc and iron pair, plunging in a diluted acid, exceeds that of a zinc and copper pair, placed under the same circumstances, although iron is more positive than copper, and can form with it a pair in which it is the positive metal. This result is evidently due to the effect of secondary polarity, which is more considerable upon copper than upon iron. In order to prove it, it is enough to employ Poggendorff's method of compensations, which does not allow of the currents being established, and which thus causes us to escape secondary polarities; in order to obtain the compensation, a Grove's pair is employed, whose electro-motive force is 22·882, and its resistance proper 5·47 units of length of a German silver wire; and the following numbers are obtained for the electro-motive forces E of the pairs, whose resistance r has been determined in each case, and which are plunged into a mixture of 1 part of sulphuric acid, and 16 parts of water.*

* The unit to which E is referred is altogether arbitrary; it depends on the pair, which is employed for establishing compensation; but its absolute value has no importance for the objects we have in view.

Pairs.	r.	E.
Amalgamated zinc, copper	52·68	13·792
" " iron	16.59	7·399
Iron, copper	12·34	6·000

Thus we see, that at all times when we do not permit the current to enter into activity, which is the case in the method of compensation, the electro-motive force of the zinc-copper pair is greater than that of the zinc-iron pair. There is likewise found for pairs of non-constant force, the law already pointed out by Mr. Wheatstone, namely, that, if we have two pairs, the electro-motive force of a third, formed of the two extreme metals of the former, is equivalent to the sum of the electro-motive forces of the two pairs, formed of the consecutive metals.* In fact, upon adding 7·399 and 6·000 in the Table above, we find 13·399, a number very near to 13·792.

After this detailed examination of the different methods employed, accompanied by some of the results obtained, we ought to indicate the electro-motive forces of the various voltaic combinations; but among the determinations that have been made we shall confine ourselves to quoting those which appear to us the best and the most important.

Poggendorff had the idea of substituting, in the Grove's and Bunsen's piles, for the nitric acid, chromic acid, which also contains much oxygen, and which abandons it easily. The solution that he employed is composed of a mixture of three parts by weight of acid chromate of potash, four of concentrated sulphuric acid, and eighteen of water. He plunged successively into this liquid, a Bunsen's carbon, platinum, and copper, the other element of the pair being amalgamated zinc, placed in a mixture of nine parts by weight of water and one of concentrated sulphuric acid; a vessel of porous clay separated the two liquids. The following is the result of three comparative experiments: —

* Vol. II. p. 793

		Resistance of the Pair.	Electro-motive Force.
Bunsen's pair	nitric acid - -	6·30	21·06
	chromic acid - -	12·28	21·61
Grove's pair	nitric acid - -	5·04	21·29
	chromic acid - -	8·30	13·42
Daniell's pair	sulphate of copper	14·72	13·63
	chromic acid - -	6·34	13·20

We see that, with platinum, the force in the pair, in which there is chromic acid, is scarcely the two-thirds of what it is with nitric acid even but little concentrated; for the nitric acid which was employed was of a density of 1·30. With carbon the electro-motive force is the same with both acids; but, besides that it is not very constant with chromic acid, the resistance of the pair with this acid is almost twice as great as with nitric acid. There is therefore no advantage in substituting chromic acid for nitric acid, although we thus avoid the nitrous vapour.

The following, for instance, are some determinations of electro-motive forces carefully made for the pairs most in use. We give for each only the means of several experiments. The electro-motive forces have been calculated by means of the formulæ $i = \frac{E}{R}$ and $i' = \frac{E}{R + l}$ which give $E = i\,i'\frac{l}{i - i'}$, i and i' being determined by the tangent galvanometer, which was placed in the circuit; the length l of the additional wire varied from 0 to 75½ yards.

		E.
Grove's pair	- - -	829
Bunsen's pair	(Delœuil) -	839
„ „	(Stohrer) -	777
Daniell's pair	- - -	470
Smee's pair	- - -	210
Wollaston's pair	- - -	208

R has also been determined for each pair by eliminating E; but this element was very variable. However, it is to be remarked, that it is much less for piles with a single liquid, in which there is not any porous diaphragm.

The following is also a determination made by M. Jacobi, according to a method founded upon the principle of derived currents, and in which, as in Wheatstone's method, the needle is brought back to the same degree of deviation in each case. He has found by four observations perfectly in accordance, that, if the electro-motive force of a Daniell's pair is expressed by 21·042, that of a Grove's pair is by 35·201; a relation, which is not very far that, which may be deduced from the Table, that precedes.

Mr. Joule has determined the electro-motive force of a great number of voltaic combinations by Fechner's process; namely, by introducing into the circuit a galvanometer, the resistance of which is very great, 300 times at least that of each pair, in order that this latter may disappear before the former, so that the electro-motive force may be regarded as proportional to the intensity of the current. The following are some of the results: —

Platinum	Nitric acid	Dissolved potash	Amalgam of potassium	302
"	"	"	Amalgam of zinc	231
"	"	"	Iron	169
"	"	"	Copper	120
"	"	"	Silver	66
"	"	"	Platinum	31
"	"	Solution of ordinary salt	Amalgam of zinc	198
"	"	"	Iron	146
"	"	"	Copper	116
"	"	"	Silver	95
"	"	"	Platinum	55
"	"	Diluted sulphuric acid	Amalgam of zinc	187
"	"	"	Iron	140
"	"	"	Copper	91
"	"	"	Silver	53
"	"	"	Platinum	37
"	Peroxide of lead with sulphuric acid	Dissolved potash	Amalgam of zinc	277
"	"	"	Iron	177

Mr. Joule thinks that we may conclude, from the Table of electro-motive forces, that he has determined, and certain alone of which we have above related, that the difference between the electro-motive forces of two positive metals, plunged into a

similar solution, is a constant quantity, whatever may be the changes that the negative elements of the pair are made to undergo.

As we see, the number of voltaic combinations whose electro-motive force has been determined is already very considerable; unfortunately, these determinations are not made after the same methods, nor upon the same plan; nevertheless, they are sufficient, in the practical point of view, and they may even also furnish, as we shall see in our last paragraph, some valuable data upon the relations that exist between chemical and electrical forces. An essential point in the theoretic relation which they enable us even now to establish is the perfectly exact proportionality that exists between the electro-motive force deduced from the intensity of the current and that concluded from the energy of the static tension, when the circuit is open instead of being closed. This proportionality is a natural consequence of the principle that we have established, by laying our foundation upon experiment; namely, that, when the condenser is charged by means of a pair, a discharge is obtained, which is a veritable elementary current.* Hence the electro-motive force of this element of the current must be the same as that of the current itself, whatever be the duration of this latter. It is M. Kohlrausch who, by accurate experiments, of which we are about to give the details, has established this important law.

M. Kohlrausch employed one of Dellmann's electroscopes, furnished with a condenser. Dellmann's electroscope is only a sort of torsion balance, the very delicate construction of which, permits of the measurement of very small forces. The condenser employed by M. Kohlrausch, was arranged in a particular manner, in order to avoid the various causes of error, which the employment of this instrument too frequently introduces. It was formed of two brass plates, about 6 in. in diameter and $\frac{1}{10}$th of an inch in thickness, each suspended by three silken cords; the cords that sustain the upper plate, about a foot in length, were attached to a

* Vol. II. p. 677.

moveable piece, which permitted of the two plates being separated or brought near to each other at pleasure. The lower plate was covered with a very thin film of gum-lac varnish, and presented at three points near to its edges three small columns of gum-lac; the upper plate rested upon these columns, when it was required to make the experiment; and was varnished at only the three corresponding points. In consequence of this arrangement, the distance of the plates and the condensing force remained constant during the whole continuance of the experiments; the mode of suspension caused the disappearance of the disturbances, that are so frequently produced by electricity, which always ends by accumulating upon the glass supports of the ordinary condensers. The lower plate played the part of the condensing plate, and communicated in general with the ground; the upper plate played the part of the collecting plate, and in order to make it communicate with the electroscope, it was merely necessary to raise it until it was made to touch a wire F, which led to the electroscope; the height of this wire was maintained constant, throughout the continuance of the experiments.

In order to charge this apparatus, he proceeded in the following manner: —

First. The upper plate was raised as far as to the wire F, and, touching the wire F with another wire, that communicated with the ground, the condenser and the electroscope were at the same time discharged.

Second. The communication of the lower plate with the ground was cut off.

Third. The upper plate was brought down upon the lower plate; and the electroscope was at the same time adjusted.

Fourth. By the movement of a mechanism, which it is useless to describe, the two plates were placed in relation with the two poles of the voltaic pair, that was being studied.

Fifth. The communications established between the plates and the poles of the voltaic pair, were cut off; and the communication of the lower plate was established with the ground.

Sixth. The plate was raised until in contact with the wire F; and the charge of the electroscope was measured.

In all this series of operations, great care was taken never to touch the metallic pieces of the apparatus with the fingers, the moisture of which might have caused an electro-motive action.

The electro-motive forces were determined by Wheatstone's method, founded upon the employment of the galvanometer and the rheostat. This measure was repeated four or five times before the application of the condenser, and four or five times after. The differences of the individual observations did not in general exceed $\frac{1}{75}$ of the mean value. The condenser was itself applied twice to each pole; and the mean was taken of the four tensions thus determined as equal to the true tension of the pair. In each case, there was observed the initial impulse communicated to the needle of Dellmann's electroscope and the torsion necessary to maintain this needle at 36° from the fixed line; the initial impulse or the square-root of the torsion might equally serve to measure the electric tension.

The following Table contains the results of the experiments: E designates in it the electro-motive force, T the tension, measured by the initial impulse, T′ the tension measured by the square-root of the torsion. In order to render the comparison of the results more easy, the observed values of T and T′, were multiplied by factors, such that the electro-motive force of the first voltaic pair inscribed in the Table, was expressed exactly by the same number as the two corresponding values of T and of T′.

Nature of the Pairs.	E.	T.	T′.
Zinc, sulphate of zinc, nitric acid of 1·357 of density, platinum - - -	28·22	28·22	28·22
Zinc, sulphate of zinc, nitric acid of 1·213 of density, platinum - - -	28·43	27·77	27·75
Zinc, sulphate of zinc, nitric acid of 1·213 of density, carbon - - -	26·29	26·15	26·19
Zinc, sulphate of zinc, sulphate of copper, copper (Daniell's pair) - -	18·81	18·88	19·06
Silver, cyanuret of potassium, sea-salt, sulphate of copper, copper - -	14·08	14·27	14·29
The same pair at the end of some time - - - - -	13·67	13·94	13·82
The same pair at the end of a longer time - - - - -	12·35	12·36	12·36

We must remark, that the rigorous accuracy with which the electro-motive force, measured by the intensity of the current, is proportional to that deduced from the energy of the tension, is due to the circumstance that the pairs are two-liquid pairs; for otherwise the tension, estimated after the circulation of the current, would not be the same as that which is observed before the circulation, on account of the secondary polarity, that would have been acquired by the negative element of the pair.

After having been engaged in all that concerns the electro-motive force of a single pair, and having pointed out the means of comparing in this respect the various pairs one with the other, it remains for us to point out the laws, which connect the electro-motive force of an assemblage of several pairs in series, constituting a pile, with that of the pairs of which it is composed. We have already seen that Wheatstone had established, by an experiment, the very simple law that, when the pairs are similar, the electro-motive force of the pile is for a pile of n pairs $n\,e$, e being the electro-motive force of one pair, and the resistance $n\,r$, r being the resistance of one pair; so that $\mathrm{I} = \frac{n\,e}{n\,r} = \frac{e}{r} = i$, I being the intensity of the current of the pile, and i that of one of its pairs. But this result is not verified, except so long as each pair with its resistance is introduced into the pile. Thus if, after having taken the intensity of the current of one pair with the sine-galvanometer, we take that of the current of a pile of n pairs, confining ourselves to introducing into its circuit the same sine-galvanometer, we shall find a much greater intensity. In order to find the same, it is necessary that each of the pairs which, by their union compose the pile, enters into its formation with a resistance equal to that which their circuit would offer, when the sine-galvanometer formed part of it. Then, the intensity of the current of n pairs in series is equal to that of one alone. In fact, we have for a single pair $i = \frac{e}{r + l}$, l being the resistance of the galvanometer; and for n pairs we have $\mathrm{I} = \frac{n\,e}{n\,r + l}$, if we place only the same

galvanometer in the circuit of the n pairs; whilst, if we place each pair, adding to it the resistance l, we have $I = \frac{n\,e}{n\,r + n\,l} = i$.

This important principle, that each pair enters into the formation of the pile with its electro-motive force and its resistance, the other pairs not being to be considered in respect to it, except as simple conductors, has been experimentally demonstrated by Fechner and by Pouillet. M. Pouillet, as we have already seen, had at first expressed the resistance of a pair by the length of a copper wire, presenting an equivalent resistance, and which he called *reduced length;* he had then found, on elongating this wire, that, conformably to the laws, which regulate the intensity of a current, this intensity, measured by the tangent-galvanometer, was in inverse ratio to the length of the circuit. Then, after having determined the individual intensity, that is to say, the electro-motive force, and the resistance proper of a certain number of pairs, he united them in series; and, having measured the intensity of the current, produced by this pile, he had found the result of experiment perfectly in accordance with that of calculation.

Thus generally, we are able to express the intensity of the current of a pile, composed of different pairs, by the formula: —

$$I = \frac{e + e' + e'' + e'''}{r + r' + r'' + r'''} \cdots$$

Since, for the pair, whose electro-motive force is e, the intensity of its current, when once it forms part of the pile, is

$i = \frac{e}{r + r' + r'' + r'''}$; for the pair e', the intensity is

$i' = \frac{e'}{r + r' + r'' + r'''}$, and so on for the rest.

Poggendorff has verified the accuracy of this law, for the case of two pairs, one Grove's, the other Daniell's, united in series, the electro-motive force and the individual resistance of which he had determined.

	lectro-motive Force.	Resistance.
Grove's pair - - - -	25·79	5·08
Daniell's pair - - - -	15·87	13·73
Piles formed by the two pairs in series { calculation -	41·66	18·81
Piles formed by the two pairs in series { experiment -	41·62	18·91

In the case, in which two or more pairs being in series, one of them is so arranged that its current must travel in a contrary direction to that of the others, it must affect its electro-motive force with the sign —, in the general expression of the intensity; but there is nothing to change in the denominator; the resistances suffering, by this inversion, no modification. However, this theoretic result is not exactly verified by experiment, except in the particular case, in which the intensity of the current is equal to 0; because there is an equality between the electro-motive forces that act in one direction and those that act in the contrary direction. In the other cases, for example, when a Grove's pair is opposed to a Daniell's pair, the stronger current, that of the Grove's pair, acts upon the more feeble pair, the Daniell's, and modifies it, by oxidising its copper, and bringing about a reduction upon its zinc, so as to diminish its electro-motive force. The definitive current, that results from the difference of the other two, is thus found to be more powerful than theory indicates, and it goes on increasing in proportion as the experiment continues, even when the pairs separated gave previously a current of constant force.*

It is therefore only in the case, in which the two opposed electrical forces are equal, that the intensity of the current is, conformably with theory, completely null, whatever in

* It follows very evidently from this, that when two pairs are opposed to each other, there is no transmission in the circuit of two contrary currents, but rather of a single one, that is produced by the difference between the force, with which one of the pairs polarises the different successive parts of the circuit, and that with which the other pair exercises the same polarisation. If these two forces are equal, the different parts of the circuit are not polarised; and there is no current at all. If things happened otherwise, the current of the more feeble pair, in traversing the stronger, ought to reduce it, as it is itself reduced by the current of the stronger pair.

other respects the resistances may be. Thus, if we oppose to each other two similar pairs, Grove's, Daniell's, Smee's, no matter what their nature, in one of which the metals have a very great surface, whilst the other has them with a very small one, a null current is obtained, although each of these pairs is able separately to produce very different effects. In fact, if we call the resistance of that with large surface r, that of the small surface, much greater according to the law of sections, will be R; but the electro-motive forces, which depend only upon the nature of the solid and liquid elements, which are the same in both pairs, are equally e for both of them; so that, even although we shall have for the former $i = \frac{e}{r}$ much greater than $i' = \frac{e}{R}$ of the latter, we shall however have $I = \frac{e-e}{r+R} = 0$, when they shall be united, by opposing one to the other.

It follows from this that, if in a pile composed of a certain number of pairs in series perfectly similar to each other, we increase the dimensions of one or of several among them, without in any way changing their nature, we in no way modify the electro-motive force of the pile, which is always the sum of the individual electro-motive forces of each pair; but we increase the force of the current or the quantity of electricity, that passes in a given time, because the total resistance of the circuit is diminished, by diminishing those of the pairs, whose dimensions have been increased. This may be verified with the pile of *fig.* 308.*, in which the hydrogen is collected, that is liberated at the negative element of each of its pairs. When the surface of one of the pairs is increased, more hydrogen is liberated upon the platinums, but always the same quantity upon each of them, according to the law of equivalents; the chemical work becomes simply more powerful upon the smaller zinc, than it was when the two zincs were equal. The reverse takes place when, instead of increasing, we diminish the dimensions of the second pair.

* Vol. II. p. 691.

Mr. Daniell, who made a great number of experiments upon piles composed of a greater or less number of pairs, measuring the volumes of the gases liberated,—experiments, the results of which were perfectly in accordance with those that are indicated by theory, remarked that, when we confine ourselves to modifying the dimension of the amalgamated zinc in a pair, without introducing any other change into this pair, the intensity of the current is not sensibly altered; because we in no way change the resistance of the pair, which depends essentially on the dimensions of the liquid conductor, and on those of the negative metal.

We have already seen that the greater or less considerable number of pairs, of which a pile is composed, only serves for giving to a same voltaic combination a greater or less electro-motive force; indeed, it follows, from all that precedes, that the number of pairs of which a pile must be composed, in order to obtain a given electro-motive force, is the converse of the electro-motive force of the voltaic combination employed. But, when once the circuit is closed, the quantity of electricity that circulates in it, is the same as that which is produced by a single pair of this same circuit, and is measured by the chemical action that takes place in this pair, that is to say, by the consumption of the positive metal which, in the entire circuit, is in a direct relation with the number of pairs, and consequently, the inverse of the electro-motive force. There would therefore be a great economy in finding voltaic combinations, the electro-motive forces and the resistances, of which were such, that a single pair, or at least a small number, produce the same effect as several. Such, for example, would be the combination,— amalgam of potassium, diluted sulphuric acid, and peroxide of lead,— which, according to Wheatstone, has the same electro-motive force as a series of five pairs,— amalgam of zinc, diluted sulphuric acid and copper. But this combination, as well as others of the same kind, is expensive; so that we prefer to make use of those, in which zinc is employed, even although it is necessary to multiply the number of pairs. However, in this case, an important question presents itself; it is to know,— two metallic surfaces

being given, amalgamated zinc and platinum,—into how many pairs we must divide them, in order to construct a pile which may produce, with a given resistance, the maximum of effect; which, for example, may decompose the maximum of water in a given voltameter, or produce the maximum of heat in a wire of a given resistance. The quantity of chemical action remains constant, since the total metallic surface, that is attacked, does not change; only, the fewer pairs there are, the more of useful effect will there be. M. Poggendorff has solved this question in a very simple manner. Calling l the exterior resistance which we are concerned in surmounting, he remarks, that we have always for one pair $i = \frac{e}{r + l}$; and, for n similar pairs, $\mathrm{I} = \frac{n\,e}{n\,r + l}$. Now, if we seek to know what value n ought to have, in order that I shall be a maximum, we find that it is necessary for it to be such that $l = n\,r$; that is to say, that the intensity of the current is at its maximum, when the total interior resistance of the pile $n\,r$ is equal to that, which it is necessary for the current to surmount exteriorly.* Hence, n is deduced by determining r and l, by means of the rheostat. It follows from this, that the maximum value of I is $\mathrm{I} = \frac{e}{2\,r}$; consequently, that the maximum of exterior useful effect, that a voltaic pile may produce, is the half of the maximum intensity that its current or that of one of its pairs may attain, when there is no exterior resistance.

If we desire to compare two piles, with regard to their maximum of useful effect, we have only to determine in each of them the maximum of intensity of the current of one of the pairs, of which it is composed; the relation of these maximums is the same as that, which is sought for. Indeed, for one this maximum is,

$$\mathrm{I} = \frac{e}{2\,r}, \text{ for the other } \mathrm{I}' = \frac{e'}{2\,r'};$$

$$\text{or } \frac{\mathrm{I}}{\mathrm{I}'} = \frac{e}{e'} \cdot \frac{r'}{r}.$$

* *Vide* final Note G.

But the maximum intensity of the current of one pair of the former pile is $i = \frac{e}{r}$; and, for the latter, $i' = \frac{e'}{r'}$. Now,

$$\frac{i}{i'} = \frac{e}{e'} \cdot \frac{r'}{r} = \frac{\mathrm{I}}{\mathrm{I}'}.$$

This result of theory is altogether in accordance with that which had been given to me, in 1830, by an experiment founded upon the simple reasoning that, in order to obtain the maximum effect, it is necessary that the number of pairs shall be such that the current should circulate in the pile neither more nor less rapidly than in the conductor that unites its poles, that consequently the resistance of the pile should be equal to that of the conductor.*

It would remain for us, in order to complete what we have to say of piles, to show that, as for a single pair, their electro-motive force estimated by the tension of the electricity, that is in the static state at each of their poles when (the circuit being open) the poles are well insulated, is exactly proportional to that which is furnished by the measures of the electricity in the dynamic state. Now, this is what follows from the first labours made by Volta, then by Coulomb and by Biot, upon the electric tension of voltaic piles which philosophers, setting out from the contact theory, have always found to be proportional to the number of the pairs, as we shall see in the following paragraph, in which we shall be occupied with this theory. Moreover, this result, which has been further verified with the new piles, is completely independent of this theory, as is proved by the analysis, that we have just made, and is in accordance with that which Kohlrausch has attained with a single pair.

Before completing this paragraph, in which we have treated upon one of the most important questions of electricity, it is impossible for us not to remark that, if the theory of electro-motive force in general and of the voltaic pile in particular does not leave much to be desired, it is not the same with the experimental determinations of the electro-motive forces and of the resistances of the various voltaic combinations which, except for some few, present but little

* *Vide* above, Vol. II. p. 233.

accordance among the results. This is due to the diversity of the methods employed, to the influence of certain disturbing causes, which we do not always know how to avoid, and finally, to the circumstances that the greater part of the processes are founded upon the employment of the rheostat; an instrument which possesses the inconvenience that the wire, which is its essential part, is not always perfectly homogeneous, and which, consequently, for equal lengths of this wire, does not always correspond to equal resistances.

Another cause of confusion in this subject is the absence of a unit adopted by all philosophers, in order to refer all electro-motive forces to it. Perhaps, in this respect, that which would be best, would be to adopt the means proposed by Weber, at the conclusion of the beautiful works executed in common with Gauss, in order to obtain an absolute measure of electric currents. This means consists in causing the current, that we desire to measure, to pass through a thick ring of copper placed in the magnetic meridian, and the resistance of which may be considered as null, in respect to that of the other parts of the circuit, in which it is placed; then, the deviation is observed of a small magnetised needle placed in the centre of this circle. If the diameter of the circle exceeds six or eight times the length of the needle, the intensity of the current is found in a manner altogether independent of the dimensions of the apparatus, and of the intensity of the magnetism of the needle, by multiplying the tangent of the observed angle of deviation ϕ, by the radius of the circle R, and by the absolute intensity of the horizontal component of terrestrial magnetism at the point of observation T, and by dividing the whole by 2π; which gives the formula $\frac{R \times T}{2\pi}$ tang. ϕ. M. Bunsen, who has employed this manner of measuring, in order to compare the electro-motive forces of his pairs with those of other pairs, had found, for Marbourg $T = 1{\cdot}88$. We shall return, when we shall be occupied with terrestrial magnetism, to this method, which has the advantage of taking in nature, that is to say, in terrestrial magnetism, the unit of which we have need.

We have said that M. Pouillet had sought for it in the current produced by a thermo-electric pair,— copper and bismuth,—the solderings of which were at 32° and at 212°. In order to compare this current with that of a simple hydro-electric pair,— copper and zinc in acidulated water,— he had at first estimated the resistance of this thermo-electric circuit, and found it equal to that of a copper wire 164 ft. in length, and 0·039 in. in diameter. Then, in order to obtain a same deviation of 16° in the galvanometer with a hydro-electric pile composed of twelve pairs, he had found that the total resistance of the circuit ought to be equal to that of a platinum wire of 590·5 ft. in length, itself equivalent to that of a copper wire of 0·039 in. in diameter, but 316,072 ft. in length. It is easy to conclude from this, that the intensity of the current produced by the twelve pairs of the hydro-electric pile is 1127 times that of the current of the thermo-electric pair; which establishes between the electro-motive force of this pair and that of a single pair of the pile the relation of 1 to 94, very near to that of 1 to 94·6 found by Wheatstone.

But it was not sufficient to have a common measure for currents. M. Pouillet also wished to satisfy himself directly of the accuracy of the principle that, for equal electro-motive forces the intensity of a current measured by its effect, that is to say, the deviation of the needle of a galvanometer is actually proportional to the quantity of electricity transmitted. With this view he placed in the circuit of a current, that traversed a sine-galvanometer, a wheel, the circumference of which, smooth like the border of a disc, presents intervals alternately of metal and of wood, these species of teeth, or of conducting and non-conducting surfaces being equal to each other. This wheel, carried upon a metallic axis, which communicates with the metallic teeth of the circumference, is able to receive an extremely rapid rotatory motion. One of the poles of the pile communicates with the axis, the other with the wire of the sine-galvanometer, which is terminated by a small tongue, that presses a little against the circumference of the wheel. During rest, when the tongue touches a metal tooth, the current passes entire, and we have, for instance, a deviation of 90°; when it touches a

wooden tooth, the current no longer passes. But, on giving a rotatory motion to the wheel, if this motion is slow, we first see the needle oscillate; then, in proportion as it is accelerated, the oscillations diminish in amplitude, and we arrive at a certain velocity, for which the needle remains perfectly fixed. Setting out from this point, we may increase the velocity indefinitely without the needle ceasing to be motionless and to mark the same deviation. In the same experiment, in which the deviation was 60° when the disc was at rest, a fixed deviation was obtained of 25° 45′, as well when the wheel made *five* turns per *minute*, as when it made *twenty* per *second*. But the sine of 60°, being double of that of 25° 45′, it follows that, by the motion, the force of the current was reduced one-half. Now, what has been done in this experiment, except reducing by one-half the time during which a current passes? and its force has thus been reduced likewise to the half. On the other hand, it is evident that the quantity of electricity, that passes in a circuit, is proportional to the time; then, a half quantity of electricity produces a half effect; and it is very true that the quantity of electricity which constitutes a current is proportional to the force of this current measured by the deviation, that it exercises over the needle of a galvanometer.

This same law is verified by taking, as we have demonstrated might be done, in order to deduce from it the quantity of electricity, the quantity of chemical action, that corresponds to it; — for example, the quantity of water, or of sulphate of copper decomposed, and placing a sine or a tangent galvanometer in the circuit. We may even establish a relation between these two manners of measuring the quantity of electricity, and thus to estimate, in units of currents, that which is required for the decomposition of a certain weight of water, one grain, for example. M. Pouillet did this by operating in the following manner: —

He commences by determining, in lengths of copper wire, the resistances of the pile, of the liquid submitted to decomposition, and of all the other conductors; then, the moment is noted, when the voltameter, that is placed in the circuit, commences the liberation of gas. The deviation of the

needle of the galvanometer, which remains constant, is observed; and the experiment is allowed to go on until a convenient volume of hydrogen is obtained, which is the only one of the two gases that is collected, for more accuracy, in order to avoid the recomposition of the gaseous mixtures. The following Table shows that the product of the time necessary for obtaining the same volume of hydrogen by the force of the current is a constant number; and this, whatever the cause may be, that makes the force of the current to vary, as well when it is the degree of conductibility of the liquid to be decomposed, or the nature of the electrodes, as when it is the power of the pile. It follows, therefore, from this (since, according to the law that we have just established, the quantity of electricity is proportional to the force of the current), that the quantity of electricity that is required for the decomposition of a certain weight of water is always the same, whether the water be more or less conducteous, or the operation lasts consequently a longer or a shorter time.

The following is the Table: —

Liquid.	Metal of the Electrodes.		Time for 2 cub. c. of Hydrogen.	Deviation of the Galvanometer.		Product of the Intensity by the Time.
	Positive.	Negative.		Angle.	Sine.	
Distilled water with sulphuric acid	Platinum	,,	498″	5°50′	0·1016	50·60
	,,	,,	501	5 40	0·0987	50·54
Former liquid diluted with one volume of distilled water	,,	,,	725	4	0·0697	50·53
	,,	,,	728	4	0·0697	50·74
	,,	,,	919	3 10	0·0552	50·73
Ordinary water with sulphuric acid	,,	,,	417	6 50	0·1190	49·62
	,,	,,	423	6 45	0·1175	49·70
	Copper	,,	251	11 20	0·1965	49·32
	,,	,,	247	11 30	0·1994	49·25
	,,	,,	247	11 30	0·1994	49·25
	Zinc	,,	239	12	0·2080	49·71
	,,	,,	258	11	0·1908	49·22
	Platinum	,,	684	4 10	0·0724	49·50
Diluted sulphuric acid	,,	,,	77	40	0·6428	49·50

Now, in order to obtain the measure of the quantity of electricity, it is necessary to know that the total resistance of the circuit, in the first two experiments of the Table, was equivalent to that of 183,631 ft. of copper wire of ·039 in. in diameter, of which 385 ft. are for the resistance of the pile and the sine-galvanometer, and 183,246 ft. for that of the liquid subjected to decomposition. With regard to the intensity of the current, it was 2665 times that of the thermo-electric sources taken for a unit, the circuit of which presents a resistance equal to that of 65·6 ft. of the same copper wire. Now, with this force of the current, there was obtained 2 cub. c. of hydrogen in 500″; and, as a gramme (15·43 grs. troy) of water contains 1241·61 cub. c. of hydrogen, there would be required, in order to bring about the decomposition, a quantity of electricity represented by

$$2665 \times \frac{1241{\cdot}61 \text{ c. c.}}{2} = 1654{\cdot}445;$$

namely, equal to more than 1600 times that which passes during 500″ in the source taken as unity; and if we take the minute for the unit of time, we find that the quantity of electricity necessary for decomposing a gramme of water, is 13,787 times the quantity of electricity that passes in one minute in a bismuth and copper circuit, whose total resistance is equal to that of a copper wire of ·039 in. in diameter and 65·6 ft. in length, and the solderings of which have a difference of 180° in temperature. And this number is always the same, whether the gramme of water belongs to a solution that is a good or a bad conductor, and whether it is decomposed by a powerful or a feeble pile.*

* M. Weber has likewise determined the absolute quantity of electricity necessary for decomposing a certain weight of water, by taking for a unit the quantity of electricity, that must pass in the unit of time (a second), through the transverse section of a conductor, which represents the unit of surface, in order to produce at a distance effects identical with those, that are produced by the quantity of magnetism that serves as the unit of measure. It is necessary, then, to observe the magnetic effect of an electric current, during the same time that it decomposes a certain quantity of water. We have already seen above, how Weber compares this magnetic effect with that of the terrestrial magnetism, at the place of observation. Unfortunately, Weber's results are not comparable with those of Pouillet, the relation btween the different units adopted by these two philosophers not having beene determined. The number found by Weber for the *electro-chemical equivalent* of water is 0·00936. He obtains it by dividing

It is probable, as we shall see in the last paragraph of this Chapter, that the quantity of electricity necessary for decomposing a gramme of water, is equal to that which is produced by its decomposition brought about by an ordinary chemical action, which explains the power of this mode of production of electricity.

Electricity of Contact.—Dry Piles.

We have already more than once made allusion to the contact theory, in which the production of electricity in the voltaic pile is attributed to the contact of two heterogeneous solid bodies, that form part of two consecutive pairs, which, in this theory, themselves constitute the pair.* We have already cited a great number of facts of a nature to demonstrate that contact in itself alone is not sufficient for liberating electricity, but that it requires, besides an action,— an action which, in the pile, is a chemical action. However, there are still a certain number of phenomena that seem at first sight incapable of explanation, except by admitting that, of itself, the contact of two heterogeneous bodies does determine, independently of all action, a development of electricity; the production of electricity in dry piles is of this number. It is these facts, that we are about to examine, in treating upon the general question of the electricity of contact.

We have already called to mind Galvani's fundamental experiment †, in which a frog properly prepared is made to undergo a sharp commotion by touching its lumbar nerve laid bare with the extremity of a wire, of copper for example, and the muscles of its thighs in like manner laid bare, with the extremity of a wire of a different metal, such as iron; these two metals themselves touching by their other extre-

the quantity of decomposed water, expressed in millegrammes (·0154 grs. T.), by the absolute quantity of corresponding electricity; estimated by means of the formula, that we have given above. In his experiments, the quantity of water decomposed was as a mean 14 m. grs. (·2156 grs. T.), and the absolute quantity of electricity, 1500 also is a mean. The duration of each experiment was about 1200 seconds.

* In the chemical theory the pair is formed of the metals, that plunge into the same liquid (see *note* of p. 661.).

† Vol. I. p. 29. (*fig.* 16.)

mity. Another more ancient experiment, devised by Sulzer, consists in placing the tongue between two discs of metal, different in their nature, one silver the other zinc, for example; then in establishing a metallic contact between them by allowing them to touch exteriorly, still leaving the tongue between the two discs. At the moment of contact a sharp taste is experienced, and there is the sensation of an instantaneous light, if the eyes are kept closed. This double effect, as well as the shock imparted to the frog, are electrical phenomena, since they can be produced in an identical manner by the direct action of electricity. Now, what is the cause of this production of electricity? It is, according to Volta, in the contact of the two heterogeneous metals; and the frog in the former experiment, the tongue in the latter, merely serve for the transmission of the electricities liberated, and for detecting their presence; that is to say, that they play no other part than that of conductors and electroscopes.

Volta then admits, that it is at the contact of two solid conductors, that the electro-motive force is developed; a force in virtue of which one of the bodies is raised into a positive state, and the other into a negative state; the two electricities, positive and negative, being necessarily equal in such sort that, if one is represented by $+e$, the other is by $-e$, $+e$ and $-e$, being added, making 0. With regard to the value of e, or which comes to the same thing, of the difference between the electric states of the two bodies, it depends upon their relative nature; but it is the same whatever be the absolute electric charge of each of them. Thus if, in their contact, two plates, one of zinc, the other of copper, acquire, the former e of positive electricity, the latter e of negative electricity, the difference between the electric states of the two plates will be $2\ e$, each of the electricities being affected by its sign. If the quantity of electricity with which the zinc is charged goes on to increase so as to be $n\ e$, that of the copper in contact with the zinc is then found to be $(n-2)\ e$, so that the difference is always $2\ e$. This second principle enables Volta to explain the accumulation of electricity in the pile. Indeed, let there be a certain number of pairs formed each of two superposed discs, one of copper

below, the other of zinc above; in each pair the copper has $(-e)$ and the zinc $(+e)$; but, if the copper communicates with the ground, its electricity is 0 and that of the zinc is $+ 2e$. Let us place these various pairs one above the other in such a manner, that the copper is always below the zinc; and let us separate the zinc of the lower pair from the copper of the upper pair by a disc of moist cloth or card, which while preventing metallic contact between the two metals, belonging to two different pairs, nevertheless allows the electricity of the first to pass to the second; we shall thus construct the column pile.* It will follow from this, that the copper of the second pair, instead of possessing an electric state 0, will have the same electric state $2e$ as the zinc of the first, and the zinc of the second will then have $+ 4e$ of electricity, by virtue of the electro-motive force, that is exerted by its contact with its copper. This $4e$ will be also the electric state of the copper of the third pair, the zinc of which will then have $+ 6e$ of electricity; and, if there are n pairs, the zinc of the last will have $+ 2ne$ of electricity, the copper of the first, which communicates with the ground, having 0. The pile in this case is charged with positive electricity only, the latter going on increasing from the base to the summit; it would only be charged with negative electricity, if the pairs had been placed in an inverse order, the zincs being below the coppers. If the two extremities or poles of the pile are both insulated, the distribution of the electricity takes place differently; one of the halves of the pile is found to be charged with negative electricity, and the other with positive. This calculation of this distribution is easily made, setting out from the same principles, and calling to mind that the sum of the free electricities, taken with their sign, both positive as well as negative, must always be equal to 0, since none has escaped away into the ground.†

* Vol. I. p. 30. (*fig.* 17.)

† The following is this calculation for the case of 8 pairs; let x be the electricity of the first copper, $2e$ being always the difference between the electric states of a copper and a zinc in contact:—

1st copper	x
1st zinc	$x + 2e$
2nd copper	$x + 2e$
2nd zinc	$x + 4e$

The direct observation made by Volta, then subsequently by Coulomb and by Biot, confirms in a very approximate manner the distribution of electricity in a pile, such as is deduced from this theory. But it is remarkable, that this distribution is exactly the same as that which we have seen to be the consequence of an entirely different hypothesis on the nature of the electro-motive force. This in fact must be the case; for that which separates the partisans of the chemical theory from those of the contact theory is the cause and the seat itself of the electro-motive force, but not the manner of regarding the mode of accumulation of the electro-motive forces of the different pairs; a point, upon which they are in accord. The only difference is, that, in the chemical theory, we merely add to each other the electro-motive forces of the different successive pairs, which must necessarily take place; whilst, in the contact theory, it is necessary to introduce an hypothesis which it is difficult to verify directly; it is that the difference between the electric states of the two metals in contact is always the same, whatever be the absolute quantity of electricity with which these two metals are charged.

As we may see, in the voltaic theory, the liquids with which the pile is charged play the part merely of conductors; they are in no way electro-motors, the origin of the electricity being entirely in the two metals of the pairs. Without dwelling upon the indirect objections against this manner of explaining the production of electricity in the pile, such as the very intimate relation that unites the quantity of electricity liberated with the quantity of chemical action produced, the necessity that the liquids should have a che-

3rd copper - - - -	$x + 4e$
3rd zinc - - - - -	$x + 6e$
4th copper - - - -	$x + 6e$
4th zinc - - - - -	$x + 8e$
Sum of the electricities	$= 0 = 8x + 32e$
Whence - - - -	$x = -4e$

This value of x being known, the electric charge of each disc is very easily found. Thus, that of the first copper being $4e$ of negative electricity, that of the fourth zinc is $4e$ of positive electricity, that of the second zinc, and of the third copper is 0, &c.

mical relation with one at least of the elements of the pair, in order that there may be an electric effect, simple conductibility not being sufficient *, points upon which we have already treated in detail, and to which it is useless to return, we shall confine ourselves to insisting upon two peremptory difficulties, that appear to us to be presented by the voltaic theory of the pile.

The first is the impossibility of drawing out a scale of the electro-motive power of solid conducting bodies. Volta had thought he had succeeded in drawing out one, in which each body was negative in its contact with those which followed, and positive with those which preceded. But this scale was true, only so long as the conductor interposed between the metals of the pair, was water or moist air; it expressed merely the greater or less facility of each body for decomposing water or for being oxidised under the combined influence of oxygen and of water. It was no longer exact, as soon as, instead of water, a concentrated acid, such as nitric acid, a dissolved sulphuret, such as sulphuret of potassium, a melted chloride, &c., was taken for a moist conductor. In one word, the order of the electro-motive powers always changes with the nature of the chemical reaction, that takes place between the metals of the pair and the liquid with which the pile is charged. Marianini and several other philosophers have endeavoured to reply to this objection, by pretending that the decomposition, brought about in the liquid, that separates the pairs, by the electricity that is produced by contact in these pairs, in depositing upon the surface of their metals foreign bodies, alters their electro-motive faculty. But if things pass thus, the nature of the electricity, taken by each metal of the pair, or which comes to the same thing, the direction of the current in the pile, ought to be the same at the first moment, what-

* Indeed, it follows, from the numerous experiments of Mr. Faraday in particular, that pairs formed of two different metals in contact are inactive even when they are plunged into the best conducting liquid, if this liquid is incapable of exercising a chemical action upon one or other of the metals of the pair; such are a pair of iron and platinum in a solution of sulphuret of potassium, a pair of iron and copper in a solution of potash, &c.

ever the liquid might be, since it could only depend upon the relative nature of the two metals. Now, it is not so; otherwise the change in the polarity of the metals of the pair takes place even when their surface is not altered, the compound, that is formed, being dissolved in proportion to its formation. Davy had already remarked the difference that exists in the direction of the current, according as the liquid conductor of a same pile is an acid solution or a liquid sulphuret. I have myself found a great number of similar examples; and Faraday has so multiplied them, that it is impossible to see anything else in Volta's scale, as we have said, than a classification of the metals, according to their degree of affinity for oxygen.

The second objection is the production of electricity in a single pair, without there being contact between the two metals, of which it is composed. We have quoted many examples of them, such in particular as that of a plate of zinc and a plate of platinum, which, plunged in acidulated water, decompose iodide of potassium, that is placed between the two plates at the place where they should have touched metallically, in order to produce electricity, according to the contact theory.* We are able, in experiments of this kind, to add this no less curious one of the production of the electric spark at the moment when contact is established between the two elements of a single pair. We are even able to render the spark very powerful by plunging into diluted sulphuric acid, two large cylindrical surfaces of copper, between which is placed one of amalgamated zinc, and connecting the zinc and the copper by means of two copper wires, which are respectively soldered to them; at the moment when, one being plunged into mercury, the other is plunged in, there is a sharp spark; the state of electric tension existed, therefore, evidently before the contact of the two metals; for, but for this, there could not possibly have been production of electricity, nor consequently of spark at the moment of the establishment of the contact; there could only have been one at the rupture.

* Vol. II. p. 668.

In the face of all these facts and of others of the same kind with which electro-chemistry abounds, the partisans of the contact theory not being able to deny the electro-motive action of liquids in the voltaic pile, have come to extending Volta's principle to the contact of liquids and solids; and even to admit that there is more electricity developed in the contact of solids and liquids than in that of solids with each other. Fechner, Karsten, Buff and Peclet have in particular done this, dwelling upon their own experiments and upon others made previously by M. Becquerel. We have already spoken of Becquerel's experiments, as well as of those of Karsten and Buff, in which the electricity liberated by plunging different solid substances into various liquids, is collected with the condenser. We have seen that they were included in the liberation of electricity which accompanies chemical actions. However, we shall return to them in a moment, at the same time that we shall speak of those of M. Peclet and of some others, the results of which do not at first sight seem in accordance with the laws, that regulate the chemical production of electricity. We ought first to examine the important question, — to know, if there is or not an electrical effect, resulting from the simple contact of two solid bodies.

Volta was not content with establishing this principle indirectly, in thus explaining both Galvani's experiment as well as that of Sulzer, and also the development of electricity in his pile. He had endeavoured to prove it by direct experiments. The following are the three modes of operating which he had devised, and which have been employed after him. Equally in all, a condenser is employed, the copper plates of which ought to be well gilded, in order to be protected against all oxidising action of the moist air.

The first mode consists in holding between the fingers, which must be moist, in order to be conductors, a plate of zinc soldered to a plate of copper, with which one of the plates of the condenser is touched*, the other being placed in communication

* We may touch directly with the plate of zinc the plate of the condenser, the latter serving as negative metal.

with the ground. The touched plate is found to be charged with negative electricity, the positive which the zinc has acquired by its contact with the copper having passed into the ground. We may in like manner place a moist conductor, such as moistened paper, upon the plate of the condensers, and touch it with the zinc, whilst we hold the plate of copper soldered to the zinc; the plate is then charged with positive electricity, whilst the negative goes into the ground. It is easy to see that these experiments are as well reconciled with the chemical theory as with that of contact, if we have regard to the chemical action, that is exercised upon the zinc, either by the moisture of the hand, or by that of the moist conductor.

The second mode of operating consists in having two insulated discs, one of zinc, the other of copper, and placing them in contact; then, in separating them, and in carrying one of them to the condenser, discharging the other; after having repeated this series of operations several times we end, when the experiment has succeeded, which is very rarely, in accumulating upon the plate of the condenser, positive electricity, when it has been touched with the disc of zinc, and with negative, when it has been touched with the disc of copper.

The third mode, which has many relations with the second, but which in general succeeds better, being less capricious, consists in taking for plates of the condenser two discs of a different nature, one of copper for example, and the other of zinc, then in connecting them by means of a small metallic arc, held by an insulating handle. This reunion being accomplished and the arc removed, we find that the disc of copper is charged with negative electricity, and that of zinc with positive electricity. We should remark that, although they may be superposed, the two discs have no other metallic contact together than that which is brought about by means of the insulated arc, on account of the layer of varnish by which they are separated.

In the two latter modes of operation, we cannot, as in the former, explain the production of electricity by the chemical

action of a liquid upon one or other of the metals in contact, since there is no liquid present. We are then obliged, in the chemical theory, to have recourse to the chemical action of the moist air. We see then how we may explain in this manner the liberation of electricity, that takes place in the third mode. We shall return again to the second. It is at first easy to prove the necessity there is, in order to obtain an electric effect, that the surface of one of the metals at least shall be in contact with the air, or with an elastic fluid, in default of a liquid. Pfaff and Fechner have indeed found that, on placing the two plates of the condenser in vacuo or in very dry oxygen, there was still an effect; but we know how difficult a matter it is, not to say an impossible one, to get free in this way of all aqueous vapours. The most sure means of avoiding all contact between the zinc and the aqueous vapour is to cover its outer surface with a layer of very thick varnish, after having taken the precaution of soldering to the zinc a small rod of platinum, which permits of the establishment of metallic communication between it and the disc of copper. If the layer of varnish is sufficiently thick, that the access of air or of moisture to the metallic surface cannot take place in any point, it is in vain to establish metallic communication between the disc of zinc and the disc of copper, or to touch the platinum soldered to the zinc with the finger, making the copper disc likewise communicate with the ground; no electric sign is obtained; nevertheless, according to the contact theory, the zinc ought to be charged with positive electricity and the copper with negative. More than this; this disc of zinc thus varnished, having become inactive, is able to serve as plate of the condenser as a plate of gilded brass, when the platinum rod, which is soldered to it, is placed in communication with an electric source; which proves that it is not for want of sensibility, that it manifests no electric signs, when it is placed in contact with the copper. Neither can we say that it is the contact with the zinc of the gum-lac, of which the varnish is made, that modifies its electric state; since the gum-lac is insulating, and since more-

over the film of varnish similar, except that it is thinner, which is upon its lower surface, does not modify it.*

Another proof of the necessity of this contact between the surface of the zinc and the air or the surrounding moisture, is that no electric sign is obtained on covering the entire surface of the disc of zinc with a film of copper or still better of gold. In other words, a plate made of gilded zinc becomes altogether inactive. However, on touching the exterior surface of this plate with the finger, I give escape into the ground to the negative electricity with which the gold is charged in its contact with the zinc, whilst the positive of the zinc is disguised and condensed by the effect of the negative electricity of the second plate of the condenser, which communicates with the ground. There ought therefore to be a charge of positive electricity in the plate of gilded zinc, and yet there is in it absolutely no electric sign. Care must be taken that the film of gold, with which the surface of the zinc is covered, shall be sufficiently thick to present no solution of continuity, that permits the moist air to have access, even in a point, to the surface of the zinc.

The necessity of an immediate contact between the surface of the oxidisable metal and the more or less moist surrounding air being well demonstrated, let us see how we may explain the production of electricity in the chemical theory. Let us take the case in which it is a disc of zinc, that forms one of the plates of the condenser; it would be the same for every other metal, susceptible of oxidising. This disc polarises the molecules of the film of moisture in contact with its surface, as a plate of zinc polarises the molecules of water in which it is immersed. At the moment when the zinc is placed in contact with the copper disc of the condenser a pair is constituted, a discharge is brought about, the negative elec-

* M. Peclet claims to have still obtained electric signs, on covering the surface of the zinc with several layers of gum-lac varnish; but we cannot be assured that the air has not had access, as far as the metal, by some solutions of continuity, until the layer is sufficiently thick for the zinc to be no longer visible. It is not necessary to increase the thickness of the layer of varnish, that is upon the condensing surface of the plate, because the air has not access to it, and, by increasing this thickness, we diminish the sensibility of the condenser.

tricity passes from the zinc into the copper in contact, the zinc oxidises, and the positive electricity, having become free being no longer able to escape, since the medium in which it is liberated, instead of being, as in the case of a true voltaic pair, liquid and a conductor, is gaseous and insulating, remains at the very surface of the zinc, where it is condensed by the negative, that has passed into the copper disc. Hence it happens that, on separating the two plates of the condenser, we find positive electricity accumulated upon the zinc, and negative upon the copper.

This explanation, which includes in a very simple manner in the chemical theory the development of electricity, that takes place in the case, in which we have just been occupied, rests upon the supposition that one of the metals of which the discs of the condenser are made, oxidises in the moist air, and that this oxidation developes sufficient electricity to charge the instrument. With regard to the first point, it is easy to prove, — we have merely to leave for a greater or less length of time a metal whose surface is very polished in contact with air even in appearance very dry, in order to perceive that this surface is tarnished, and this, even when very slightly oxidisable metals are in question, such as copper and silver. With regard to the second, it follows, from the experiments of Faraday and of Becquerel, made in an entirely different, manner, and which we shall relate in the following paragraph that the proportion in which it suffices that a metal shall oxidise, in order to liberate a quantity of electricity, capable of charging a condenser, is infinitely small, since the decomposition of a single milligramme (·015 grs. T.) of water resulting from the oxidation of a quantity of metal equivalent to about ·06 grs. T. for the zinc, produces sufficient electricity to charge 20,000 times a magic pane, the coated surfaces of which still exceed a square yard, so that each charge shall give a spark ·393 in. in length, the oxidation of ·015 grs. T. of zinc would therefore charge it only 5,000 times. Now, in order to charge a condenser without sensible spark, but only in a manner to cause the gold leaves of the electroscope to diverge, the $\frac{1}{10,000}$th part of the charge, that

gives a spark of ·3937 in., would suffice; consequently, the oxidation of ·000015 gr. of zinc would produce sufficient electricity to charge the condenser 5,000 times. Hence we may comprehend how difficult a matter it is to avoid the very feeble oxidation, that is sufficient to produce the electricity, that is detected by a condenser. We may further remark, that the extent of the metallic surface, that is in contact with the oxidising medium, exercises no influence over the charge of the condenser, which depends, as we have seen, only upon the intensity of the electro-motive force, which arises from the mutual action of this medium and the metal; this explains why it needs but a few points of this surface to be in contact with the medium, in order that the condenser may be charged.

We may further add, that even although the positive metal should not be susceptible of oxidising in the open air, in its natural state, the fact that it is united metallically to another metal, which forms the second plate of the condenser, of which it is itself the first, facilitates its oxidation, exactly in the same manner as it is facilitated when this metal, plunged in an electrolytic liquid, is united metallically with a metal less attackable, which plunges into the same liquid.* The only difference is, that there is merely a single discharge, instead of a continuous current; but we have proved that this in no way changes the nature of the phenomena that take place.†

It is useless now to quote the numerous experiments by which Fechner, Pfaff, Belli, and so many others have endeavoured to demonstrate the truth of Volta's theory by means of the third manner of operating, which we have analysed; since the result of these experiments is not in

* Vol. II. p. 676.

† It would be very interesting to combine an apparatus, that enables us to charge and to discharge very rapidly and a great number of times consecutively a condenser, of which one of the plates should be of very polished zinc; and to see if the plate would not be more oxidised than a similar plate left quite insulated in the same medium. Moreover, the great rapidity with which the metals, such as iron, oxidise in the air, when they are in contact with a less oxidisable metal, such as lead or copper, allow of no doubt upon the result of the experiment.

opposition to the chemical theory, as we have just demonstrated. We shall dwell only upon certain facts which seem to conform to it less easily.

M. Peltier, having taken for plates of a condenser, a disc of gold and a disc of platinum, and having made them communicate by means of an insulated platinum wire, found that the former was charged with positive electricity, and the latter with negative electricity. Having then prepared four glass discs, one covered with platinum foil, the second with gold leaf, the third with silver leaf, and the fourth with tin foil, he employed them, by combining them one with the other, two and two, as plates of a condenser; and he found, on placing them in communication with a same source of electricity, that some are more easily charged with negative electricity than others; whence he concludes, that there exists between the metals a difference with regard to their faculty of coercing the same electricity. Thus the four metals tried ought to be placed in the following order, with regard to their faculty of coercing negative electricity: platinum, silver, gold and tin. M. Peltier had also concluded from his researches that, in their state of natural equilibrium, the metals possess different quantities of electricity, whether positive or negative, according to their nature; and that it is to this electricity, inherent in the particles of the metals, and which is inseparable from them, that the electric effects of contact would be due, in which no trace of chemical action is perceived. But it is easy to see that all the effects observed by M. Peltier are due to an opposition between the electromotive forces of the sources, with which the condenser is charged, and that which arises from the contact of the moist air with the metals of which the plates of the condenser are made. Nevertheless, the fact of the negative charge, that is acquired by the platinum disc in its contact with the disc of gold, deserves to fix for a moment our attention.

M. Becquerel has obtained the same result as Peltier; but, on the other side, on employing a condenser made of two plates of platinum, he observed no electric sign, on touching one of the plates with a plate of gold, held in one hand, and

touching the other plate with a finger moistened with distilled water. In the case observed by M. Peltier, and verified by M. Becquerel, it is not therefore the contact of the gold and the platinum, that determines the electric charge. We are indebted to M. E. Becquerel for an experiment, which has put us in the way to the true explanation of the fact in question. A condenser, whose two plates are of platinum, gives no sign on the electroscope, when they are touched with the finger; but if one of the plates is removed, and is plunged for a few moments in hydrogen, we find, after having replaced it, and having established metallic communication between the two plates, that the one, which has been in the hydrogen, is charged with positive electricity, and the other with negative. This effect lasts for some time, then diminishes little by little, in consequence of the plates remaining in the atmospheric air. At each new immersion of the plate in hydrogen, the same result is obtained.

This double property of platinum being sometimes positive, sometimes negative, according as its surface is covered with hydrogen or oxygen *, is due without any doubt to the faculty that is possessed by this metal of bringing about the combination of oxygen and hydrogen by its contact with these gases, and even the decomposition of water, as in Grove's gas pile, when it is in contact with one of these gases and water. The disc covered with hydrogen behaves, therefore, as a positive disc of zinc, that might form one of the plates of the condenser, the other being a disc of ordinary platinum. The platinum disc, that has not been plunged in hydrogen, but simply in atmospheric air, condenses at its surface oxygen, as we have established †; whether this gas forms a slight film of oxide, or remains in the gaseous state upon the surface of the platinum, is of little importance; in every case, it acts under the influence of the platinum upon the aqueous vapour in contact with it, and decomposes it; it is an effect of secondary polarity, analogous also to that, which takes place in the gas-pile. It should follow from this, that

* We say oxygen, although it is in reality atmospheric air; but this comes to the same thing.

† Vol. II. p. 415. and the following.

the platinum disc, when it is placed in contact with a disc of gold, these two discs, forming the plates of a condenser, ought to give to this disc positive electricity, and retain the negative. If the plates of the condenser are both similar discs of platinum, and both of them consequently covered with oxygen, there is no effect. The contact of a plate of gold, that is held between the fingers, with one of the discs, ought no longer to give rise to any electric sign, if our explanation is exact, since the two platinum discs are always identical; now, this is precisely what arises contrary to what ought to take place, if contact were the cause of the electricity, liberated in the case, in which the two discs are one of gold, and the other of platinum. If the quantity of chemical action is very feeble, let us not, on the other hand, lose sight of—how infinitely small is the quantity of electricity necessary for charging the condenser.

It is to a cause of the same kind that must be attributed the development of electricity, that takes place in the contact of platinum, or of gold and of peroxides, such as that of lead or of manganese. It is sufficient, in order to prove that it is not an effect of contact, to place between the disc of the condenser and the peroxide a plate of thin wood, and still sufficiently conducteous, although dried; then, on touching the peroxide with the moist finger, or with a piece of paper steeped in an acid or an alkaline solution, the plate of the condenser is charged with positive electricity. It is charged with negative on interposing between it and the peroxide moistened paper, and on touching it with the piece of dry wood, that is held between the fingers. Thus, in the chemical action that is exerted by the peroxide of manganese, or that of lead upon moist bodies, the positive electricity remains in the peroxide, from which it passes into solid and conducting bodies in contact with it, whilst the negative passes into the moist bodies. The dynamic effects, to which the immersion of a peroxide and a plate of platinum, fixed respectively to the two extremities of a galvanometer, into pure water, or still better into acidulated water, gives rise, are altogether in accordance with the facts that we have been just describing,

as it results, as we have seen *, from the researches that M. Becquerel and myself have made upon this subject. Mr. Faraday has likewise arrived at the same conclusion, by showing that bodies extremely charged with oxygen, such as the peroxides, very freely exercise chemical actions, especially when they form, as in the cases, which have just engaged our attention, one of the elements of a pair. With regard to the platinum, we know that, even when the quantity of oxygen condensed upon its surface is very feeble, it always behaves in all phenomena of this order as a body quite ready to part with its oxygen.†

It appears to us, therefore, well established that, in the contact of two solid bodies, the electricity developed is not due to the fact of this contact; since, when we succeed in avoiding all chemical action, which is very difficult, it is true, there is no electric sign, even when all the conditions necessary to there being one in the contact theory are united. It is clear that we must also avoid the other actions, that may give rise to electricity, such as calorific and mechanical actions. Indeed, we have seen, when engaged with thermo-electricity, that the contact of a hot and of a cold body produces an electric current; but this effect is in no degree due to the contact, which is here, as in the electricity engaged by chemical actions, only a manner of permitting the electricity, developed by the molecular changes that accompany the propagation of heat to manifest themselves. We must likewise avoid, in the contact of bodies, the mechanical actions, which, in themselves producing electricity, may give rise to errors; it is especially when we operate according to the second mode pointed out by Volta, by placing in contact discs held by insulating handles, that this precaution is necessary, as we are about to see, when occupying ourselves with this mode.‡

* Vol. II. p. 681.

† Vol. II. p. 415. and following pages.

‡ However, we must also have regard to this cause of error, when we operate according to the first mode, by holding between the fingers the bodies that are placed in contact with one of the plates of the condenser. We know in fact that the very slightest friction, exercised upon this body by the fingers, especially when they are dry, is sufficient to liberate a very considerable quantity (see above, p. 605.)

The mode in question consists therefore of placing in contact several times in succession an insulated disc of zinc and one of copper, each time bringing one of them to the condenser, whilst the other is discharged. Fechner has remarked that, if one of the two discs, that of zinc for example, is fixed to an electroscope, and the other, that of copper, is placed above, as the second plate of a condenser, but without an insulating stratum, a very sensible positive electricity is obtained on the electroscope on raising the copper disc, whilst when they are in contact, there are no sensible electrical signs, even when the copper communicates with the ground. Pfaff and Peclet attribute this effect to the fact, that the two discs, not being very smooth, they are in contact only in certain points, and that everywhere else they are separated by a stratum of air, which fills the office of insulating stratum, so that there is a condenser. M. Peclet has observed several facts which have proved to him that discs in contact may behave as air condensers; he has remarked that, if they are very smooth, so that there is difficulty in separating them,— a proof that there is no film of air interposed,— there is no electricity developed, whilst there is a notable production if their surfaces are ground with emery and deformed so as to be no longer smooth. MM. Fechner and Buff cannot agree with the explanation of Pfaff and Peclet; they are rather disposed to admit, on the contrary, that it is especially at the points of contact that the accumulation and condensation of the electricity are the most considerable, Fechner having remarked, contrary to Peclet, that the electricities are condensed more in proportion as the two faces are polished. But these differences possess little importance in opposition to the fact observed by Mr. Grove, namely, that the experiment of the two discs succeeds equally well, even when there is no metallic contact between the discs, which he obtains by placing between them a thin ring of card, which does not prevent of their approaching as much as possible toward each other, but still avoiding metallic contact. We have thus a true condenser with a plate of air for insulating stratum, only we make neither of the two discs communicate with the ground, which makes it

necessary for them to be brought several times to each other in order to charge a true condenser. It is of little importance therefore whether the discs act as condensers; as we are, however, inclined to believe in the experiments of Fechner and Peclet, the cause of the liberation is not the less the same as in the experiments made with condensers, the plates of which are of two different metals; we have therefore no need to return to it.

But, as we have said, it is important, in this mode of operating, to avoid mechanical actions and particularly friction, which may give rise to grave errors upon the origin of the electricity liberated. M. Becquerel has shown this, on repeating the experiments from which Davy had thought he could conclude that metals could acquire positive electricity in their contact with the acids, and negative electricity in their contact with the alkalies; the acids and the alkalies acquiring contrary electricities to those of the metals. Davy operated with solid acids and alkalies, such as oxalic acid, succinic acid, and boracic acid, dry lime, magnesia or strontian; the metals were copper, zinc, tin, held by insulating handles. These facts, from which Davy had thought he could deduce important consequences on the nature of the electricity inherent to acids and to bases, were only effects of friction, as Becquerel has proved. He has adapted to a very sensitive electroscope a condenser formed of discs of platinum; he never obtained any effect on placing upon one of the plates of the condenser a piece of very dry lime held between the fingers, and on touching the other plate also with the finger. He then placed the piece of lime upon a plank of very dry wood, then he carefully placed upon it without exciting friction, a copper disc held by an insulating handle; he withdrew it, then placed it in contact with one of the plates of the condenser, touching the other with the finger. On repeating similar contacts a certain number of times, he never obtained any electric charge; but if, instead of placing the disc of copper upon the lime with precaution, it is placed with friction, we succeed in charging the condenser after a small number of contacts; the entire charge is the more

marked as the friction has been stronger; the lime acquires positive electricity, and the metals negative. On substituting for the lime one of the acids above mentioned, a charge of electricity is in like manner obtained by friction and not by simple contact; in this case, the metal acquires positive electricity, and the acid negative. It is therefore well demonstrated, that the results obtained by Davy are due to electric effects of friction, and not to Volta's electro-motive action.

The analysis, that we have been making of the electric effects, that are manifested in the contact of two solid bodies, confirms the conclusion that we have drawn from facts of quite another order; namely, that, in a voltaic pair, the origin of the electricity is not in the contact of the two metals, of which the pair is formed. It is therefore in the action, that takes place at the contact of the liquid and the metals. The following is an interesting experiment of Peltier's, which shows in an evident manner where the seat of the origin of the electricity is situated in a pair.

The extremities of a zinc and copper pair (*fig.* 325.) are

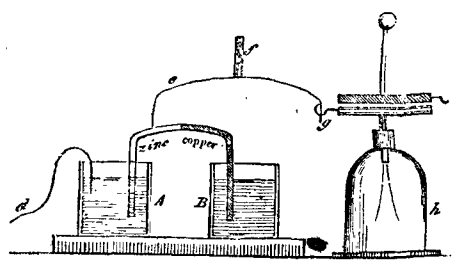


Fig. 325.

plunged into two vessels, separated and well insulated, and filled with the same liquid. The end of a platinum wire *d* is first immersed in the vessel A, that has received the zinc, and the other end of the wire communicates with the ground. By means of another platinum wire *e*, which is held insulated by a handle of gum-lac *f*, the zinc, the copper and the liquid of the vessel B, that has received the copper, are placed successively in communication with one of the condensing plates *g* of an electrometer *h*. According to this arrangement the liquid is unable to possess

free electricity, since it communicates with the ground; neither ought the zinc to possess any, since the electro-motive force, according to the theory of Volta, is at the contact of the zinc and the copper. It is not thus that the distribution is brought about; the liquid of the vessel A is neutral; but the zinc, the copper, and the liquid B are negative in the same degree. The end *d*, of the platinum wire communicating with the ground, is then placed in the vessel B, and the copper, the zinc and the liquid of the vessel A, which is then insulated, are interrupted in the same manner, by means of the insulated platinum wire *e*. The liquid of B is necessarily neutral, as well as the copper that is plunged into it; but it is the same with the zinc, which is equally neutral: the water alone of the vessel A is positive. This experiment proves, therefore, that the electricity is not produced at the contact of the two metals; but rather at the contact between the acidulated liquid A, and the portion of zinc that is immersed in it.

The partisans of the contact theory have therefore been led to establish that it is in the contact of liquids and solids that the principal source of electricity resides; but still without recognising that the chemical action, which takes place between the solid and the liquid was the cause of the electricity liberated, admitting that it is simply its effect. Numerous experiments have been made upon the production of electricity, that takes place in the contact of solids and liquids; we have already cited those of Becquerel, which are the most ancient, and those of Karsten and Buff. We may call to mind that those of Becquerel consisted in placing upon the plate of the condenser a metal capsule, what was filled with different liquids, into which various metals held between the fingers were plunged. When the capsule was of platinum, whatever was the metal employed, and whatever was the solution, acid or alkaline, the liquid was always charged with positive electricity, which passed through the platinum capsule, and charged the condenser. When the capsule was of copper, it acquired positive electricity, if (the solution being acid or alkaline) the plunged metals were zinc or iron; it acquired negative if, in the same solutions,

the immersed metals were platinum, gold, or silver. All these effects are perfectly in accordance with the chemical theory. With regard to the effects observed by M. Karsten, they also enter into the same theory; but we shall not dwell upon those which (of the same kind as the results obtained by Becquerel) have already equally been the subject of our examination; the others have been obtained by combining the electricity produced by the immersion of zinc and copper pairs in liquids more or less acid, with that developed upon condensers, of which one of the plates was zinc, and the other copper. Effects of a more or less complex character are the result of this, the explanation of which is easily found by means of the principles that we have established in what precedes; and upon which consequently it is useless for us to insist. We may only remark, that the electromotive or polarising force, which arises from the contact of a metal, as zinc with the simple vapour of water, is able to contend against that, which arises from the contact of the same metal with pure water, but is inferior to that which is manifested when the water is acid, alkaline, or saline. This important principle must not be lost sight of when we are endeavouring to reconcile with the chemical theory facts, such as some of those observed by Karsten, which have frequently been put forward as contrary to this theory.

Among the philosophers who have been much occupied with the electricity liberated in the contact of solids and liquids, we have cited M. Peclet. This philosopher operated either with an ordinary condenser, or, for cases in which the electricity was feeble, with his multiplier-condenser, that we have described.* He touched the upper plate with the metal, and collected the electricity of the lower, so that the electricity given by the metal, was of a contrary sign to that which had been collected. In order to have the action of the same liquid upon the metal, he took each metal between his fingers, after having moistened them with each of the liquids successively. The following is a Table, that contains the results of his experiments. We have chosen it among all

* Vol. I. p. 107.

those, which have been drawn out on this same subject, by various philosophers, as the most exact and the most complete.

	Zinc.	Mercury.	Lead.	Tin.	Iron.	Antimony.	Bismuth.	Copper.	Nickel.	Silver.	Platinum.	Gold.	Carbon.	Peroxide of Manganese.
Pure water. - -	+26	+26	+17·5	+15	+11·5	+8·7	+7·3	+7·3	+10	,,	,,	,,	,,	−15
Diluted sulphuric acid - - -	+27	+27	+14	+16	+13	+7	+ 4	+2·5	+3	,,	−6	−4	−3	−20
Diluted nitric acid	+26	+21	+13	+12	+ 8	+1	+ 1	,,	+0·5	−2	−4	−4	−3	−21
Hydro-chloric acid	+26	+20	+13	+12	+11	+5	+ 5	+5	+6	−3	−2	−0·3	−4	−21
Aqua regia - -	+27	+16	+15	,,	+12	+6	+ 3	+3	+4	+2	−4	−4	−4	−19
Solution of potash	+30	+28	+24	+28	+19·5	+21·3	+ 1·7	−11·7	+10	+3·5	+5	+5	+4	−7
Ammonia - -	+38	+26	+22	+22	+13	+16	+10·5	+11·5	+8	+3·5	+4	+4	+3	−4
Sulph-hydrate of potash - -	+30	+35	+17·5	+24	+17·5	+20	+18	+22·5	+20	+22·5	+17	+17	+13	+5
Solution of sea-salt	+25	+22	+14	+15	+15	+7	+ 6	+6	+6	+2·5	,,	−4	−2	−13
Alcohol - -	+26	+22	+13·5	+13·5	+ 6·5	+7	+ 4	+5	+3	,,	,,	,,	,,	−9·15
Olive oil - -	+35	+12·5	+20	+0	+ 9	−10	+ 7·5	+7·5	+5	,,	,,	,,	,,	−10
Oil of naphtha -	+24	+12·5	+13·5	+14·5	+10	+7·5	+ 9	+3·5	+4·5	,,	,,	,,	,,	−11

We see from this Table that in general, save rare exceptions, the electricity collected was always positive, which indicates that that given by the metal to the condenser was negative, and that consequently this metal was attacked by the liquid, with which the fingers were moistened. The peroxide of manganese alone presents an exception; but this is due, as we have said, to the fact that the chemical action which takes place in its contact with liquids is a deoxidation; and consequently ought to produce an electricity, contrary to that which results from oxidation.* Silver, platinum, gold, and carbon, also gave with acidulated water, electric signs, contrary to those which would have been produced had their oxidation taken place; these signs are, it is true, very feeble; and the assistance of a multiplier-condenser was necessary in order to collect them. They are evidently the result of the action that is exercised upon the fingers themselves by the slightly acid liquid with which they are moistened, — an action which is not counterbalanced, in the case in which the

* There is only one case in which the peroxide of manganese transmits negative electricity to the upper plate, and consequently positive to the lower; it is that in which it is in contact with sulf-hydrate of potash. This is due to the particular nature of the chemical action, which takes place in this case, an action probably very complicated, because there is at the same time a decomposition of the peroxide and of the sulf-hydrate.

metals are but little or not at all oxidizable, by that which these metals themselves suffer. The positive electricity, taken by the acidulated water in its action upon the finger, is transmitted by the intervention of the metal to the upper plate of the condenser, and charges the lower with negative electricity, as is shown by experiment.

The effects obtained with alcohol and especially with olive oil and with oil of naphtha, appear at the first moment surprising, considering the nature of these substances; but it is evident that they do not moisten the fingers sufficiently to form an insulating film; but for this there would be no electric signs, since there would be no communication with the ground; the oils form probably with the alkaline transpiration, with which the fingers are in general moistened, a compound that is a conductor, and that acts upon the metals; — an action, which is very far from being null, as we are every day assured, by observing the metallic rusts that are impregnated with oil.

Let us remark in passing, that in the electric effects of contact, we should have done wrong, when such feeble electric signs are in question, not to have taken sufficient account of the electricity that results from the chemical action *upon* and *by* the fingers, that are employed in the experiments. We have already remarked the important part that is played by this action in the development of the electricity, that is obtained on touching a condenser by a metal, held between the fingers; we have just seen in Peclet's experiments the effect that results from the action upon the fingers of certain liquids. We shall see hereafter, when occupying ourselves with animal electricity, how important it is to have regard to this cause of production of electricity, if we would avoid falling into grave errors.

We have said that M. Buff has also made numerous researches upon the electricity developed in the contact of metals and of liquids. We have already spoken of effects of this nature, which he had obtained in the experiments, wherein he had demonstrated that evaporation is not itself a source of electricity; but that it serves merely to render

more perceptible, by the conducting faculty of the vapour formed, the electricity liberated by the action of a liquid upon a metal. Like Karsten, he had remarked that, on collecting the negative electricity arising from a zinc wire, immersed in the liquid, with a zinc condenser, he obtained less effect than when the conductor was of copper; which is due, as we have said, to the opposition of the two electro-motive forces, exerted one by the solution upon the zinc, that is immersed in it, and the other by the moist air upon the plate of zinc. On placing successively, upon condensers made of various metals, liquids of various natures, he had obtained results analogous to those of Becquerel and of Peclet; and he had deduced from them consequences, altogether in opposition to the law of the voltaic series of electric tensions. He had been thus led to connect the electro-motive force with the chemical affinity of the metal for the radical of the compound liquid, with which it is in contact; and consequently to see in the development of voltaic electricity, a chemical phenomenon and not a simple effect of contact.

To sum up, it seems to us to result from the numerous researches, that have been made upon the cause of voltaic electricity; — researches of which we have been enabled to give only a summary extract; that, in order that this electricity may be developed as well under the static as under the dynamic form, it is necessary that there shall be a chemical relation between the bodies in contact,—a relation such that one of them is able to enter into combination with the other, or at least with one of the elements of the other.

It remains for us now to demonstrate that dry piles are not an exception to this principle, and that it is truly chemical action, and not contact, as has been pretended, which is the origin of their electric power.

We have already described summarily dry piles *; we may add to what we have already said upon this subject, that the fundamental idea of dry piles rested upon the voltaic theory of the pile. It was hoped there might be found, for separating the pairs, a conductor at the same time

* Vol. I. p. 52.

not a liquid, and not an electro-motor, in such sort that the pile might have continually given electricity, without sensibly altering; it was, to speak frankly, seeking to realise the idea of perpetual motion, to hope to produce a constant force by a simple arrangement of substances without corresponding expense or work. The results have also been as poor as the principle was vicious. Piles have been obtained, the power of which was able to last for a very long time, still however having a limit; but it was at the same time very restricted; since these piles gave only the effects of tension, and were incapable of producing currents, save in certain exceptional cases.

The first dry pile was constructed by Behrens in 1805; it was composed of eighty pairs of zinc, copper and gilded paper; Deluc in 1810 made several attempts of the same kind, and succeeded in uniting 800 pairs, formed with discs even of tinned iron and of gilded paper; the tinned iron and the gilding of the paper formed the two metals of the pair, and the paper was its moist conductor. This pile caused the leaves of an electroscope to diverge powerfully at its poles. Finally, Zamboni in 1812, constructed the dry pile according to the mode, which has been generally adopted, namely, by forming it of the super-position of a very great number of discs, made of paper, covered on one of their sides with a thin layer of tin, and on the other with a layer of peroxide of manganese in fine powder, fixed upon the paper by honey or starch paste. A pile formed of 2000 pairs of this kind gives small sparks, is able to charge a Leyden jar, &c. With similar piles placed vertically, one beside the other, at a little distance apart, and so that their opposite poles are facing, a continuous backward and forward motion may be imparted to a small insulated pendulum, that oscillates between the two contrary poles. All dry piles, we have said, lose their power with time; but those which last longest, at the same time being less powerful than those of Zamboni, are piles constructed with superposed discs of Dutch-silver paper, and Dutch-gold paper. We must stick together by the surface, where the paper is bare, the discs of different species, so that on super-posing them, we have, for example, Dutch-gold,

paper, Dutch-silver, Dutch-gold, paper, and so on, taking care always to observe the same order. The discs are attached together by means of cords made of a very pure silk, so that it may be very insulating, and well impregnated with varnish; we may also elevate the pile between varnished rods of glass, and press it by means of a screw enclosing it in tubes of varnished glass, of which the bottom whereon the first disc rests is metallic, whilst the last disc is pressed by a metallic screw, terminated exteriorly by a ball. The size of the discs influences the velocity with which the pile is charged; but is without influence upon the tension of its poles. M. Riess, with four piles of this kind, each of 2,230 pairs of an inch in diameter, obtained as a mean, on placing them one beside the other, so that their contrary poles were opposite, ninety-six small sparks of ·0049 in. in length, per minute. Four months after they had been constructed, they gave no more than forty-eight sparks per minute. Jäger and Singer, who have been much occupied with dry piles, had succeeded not only in producing by their means, powerful movements of attraction and repulsion, as well as sparks, but also in charging Leyden jars; however, they had not succeeded in obtaining chemical decompositions, nor effects of deviation on the magnetised needle or contractions of the frog properly prepared. However, Dubois-Reymond has obtained these last two kinds of effect with a pile of 1800 discs, similar moreover to those which Riess employed. It was necessary that the frog should be freshly prepared; and with regard to the multiplier, it was of 24,160 turns, and it indicated a deviation of only a few degrees. Riess, on his side, has decomposed iodide of potassium, sulphate of soda, and nitrate of baryta, with an old dry pile of small dimensions.

M. Peltier, and more recently M. Delezenne have easily obtained the decomposition of water, by means of dry piles, by giving to their discs a large surface, so as thus to diminish the resistance. M. Delezenne, in particular, employed piles of 2000 pairs, each pair being a rectangle of 12½ in. in length by 7 in. in width. The pairs of these piles were of paper, tinned on

one side, and covered on its other face with peroxide of manganese, rubbed in gelatine in fusion. If the number of pairs is too considerable, sparks are obtained; but, according to Peltier, there are no calorific effects, nor decompositions; however, Delezenne has easily decomposed water with piles of 2600 and of 4000 pairs. The same philosopher has made a great number of experiments, in order to demonstrate the necessity that the paper of the discs should not be too dry; he moistened them with salt water, so as to obtain the presence of the salt, which on maintaining their moisture, increased their electric power; he then powerfully dried the piles by placing them in ovens which at first increased their power, probably on account of the fusion of the gelatine glue, but which afterwards greatly reduced it, the glue having become solid again, by the effect of the absence of moisture. Finally, he saw that in order to maintain a tolerably considerable power in the pile, it was necessary from time to time to renew the stratum of peroxide of manganese which was evidently deoxidised, and he perceived that the tinned face was slightly oxidised.

All observers have agreed in recognising that moisture is necessary, in order to preserve to dry piles their activity. An experiment of Ermann's, confirmed by Jäger and by Parrot, proves this in an evident manner. A very active dry pile, having been placed in a vessel, the air of which had been completely dried by chloride of calcium, entirely lost its force in a few hours, and recovered it again in the moist air. Parrot made a great number of experiments, in which the dry piles were rendered alternately inactive or active, accordingly as they were placed in dried or in moist air. However we must not conclude from the fact of moisture being indispensable to the dry pile, in order to produce its electric effect, that it is in very moist air that this effect is the most powerful; for there is then a defect of insulation, which militates against electric manifestations.

We may add that Jäger has constructed dry piles, by interposing between the metal layers in contact layers of resin or of silk; but these piles are only a series of condensers, which have no relation with the pile properly so called,

and for the action of which the moisture of the air is nevertheless always necessary.

Watkins succeeded also in constructing a dry pile with a single metal, presenting it is true two different surfaces. It is composed of 60 or 80 plates of zinc of about 4 square inches of surface, cleaned and polished on one of their faces and not on the other. They are fixed in a wooden trough, parallel to each other, at only $\frac{1}{20}$ of an inch distant from each other, the polished faces being all turned on the same side. The two extremities or poles of this pile give very decided signs of electric tension, of a nature to indicate that the polished face plays the part of positive metal, and the unpolished that of negative metal. The humidity of the air favours the development of electricity in this pile, in which the thin stratum of air, by which the plates are separated, plays the part of moist conductor, like the paper in the ordinary dry piles, which is perfectly in accordance with the manner in which we have explained the liberation of electricity in condensers, of which one of the plates is of zinc and the other of copper, or of zinc covered with a layer of varnish, sufficiently thick for the air not to be able to penetrate as far as its surface.

It is not necessary to insist long, in order to show that dry piles are all equally apparatus, in which the development of the electricity is due to a chemical action exercised by the paper, as by the moist air upon the substances, whose union constitutes the pairs. With regard to the nature of the effects, that they are susceptible of producing, it depends especially upon the very considerable resistance to conductibility, that is presented by these piles, even more than upon their electro-motive forces, which are tolerably energetic. These piles have a certain relation to water piles, such as that of Gassiot's of 3520 pairs, which have much tension, but do not give very considerable dynamic effects, on account of the great resistance which they present to the circulation of the current. Now, as we have seen, Gassiot has very well established the chemical theory of his water-pile; and in like manner as the presence of moisture is

necessary to the dry pile in order to its being in action, so also the presence of air or rather of oxygen is indispensable to the water-pile; because like as dry air is not able to act chemically on the majority of the metals, so also water deprived of oxygen is equally without action; a proof, equally in both cases, of the necessity of a chemical action.

Relations between Electricity and Chemical Actions.—Electro-chemical Theories.

Let us consider a voltaic pile, the closed circuit of which includes a voltameter; suppose that this pile is *fig.* 308., so constructed, that we collect the hydrogen liberated at each pair, and are able to estimate the quantity of zinc oxidised. Two orders of phenomena are presented to us in this circuit; an equivalent chemical action exercised wherever there is a liquid conductor susceptible of being decomposed, — a production of electricity, which is manifested exteriorly by the influence, that is exercised upon a magnetised needle by all the parts of the circuit. The arrangement given to the various metallic and liquid parts of which the pile is composed, permit at the same time of the exercise of affinity, and of the production of electricity, that accompanies it. It is evident that the origin of these two forces is in the surface of contact of the zincs, and the liquid, and that the equivalent chemical action, which takes place in the voltameter, is only the result of the action at a distance of affinity. Indeed, when once all the parts of the circuit, the solids as well as the liquids, are polarised by the combined action of all the zincs upon the electrolytic liquid by which they are bathed, it is necessary, in order that the discharge may take place, and that the water may be decomposed between the metals of each pair, that it be also decomposed between the two platinum electrodes of the voltameter; otherwise the circuit would not be closed. But then, there is a resistance to be overcome, since of themselves the two electrodes are without action upon the liquid of the voltameter. This resistance is surmounted by the electromotive force, the intensity of which depends upon the relative nature of the

liquids and metals of the pair, and on the number of these pairs. It is true that it varies also for a same electro-motive force, with the nature of the metal of which the electrodes of the voltameter are made. It is clear that if the positive electrode is of zinc, the negative remaining of platinum, not only is there no longer any resistance, but there is an increase in the electro-motive force, since there is one pair more. If the electrodes are both of zinc, or of a similar oxidisable metal, it seems that the resistance ought to be the same as with platinum electrodes, because the two zincs tend to polarise the electrolytic liquid in contrary directions with a same intensity; and that consequently, their effect, in respect to the facility introduced for the decomposition of the liquid, is annihilated. However, things do not take place in this way, and this is due to the circumstance that the oxygen, which is liberated at the positive electrode, instead of forming, as upon the platinum, an adhering film, which hinders the passage of the current and produces a secondary polarity, combines with the metal of the electrode, forming an oxide, which is dissolved. With regard to the hydrogen, that is liberated at the negative electrode, it is in general likewise absorbed by the reduction of this electrode, which is most commonly oxidised, or by its combination, under the influence of the electrode, with the dissolved oxygen. However it is principally at the positive electrode that the advantage is felt, for the propagation of the current in the circuit, of taking for this electrode, a substance, capable of combining with the element of the electrolytic liquid that is liberated, forming with it a compound soluble in this liquid.

There is, therefore, in a voltaic circuit, of which the voltameter forms part, decomposition of water in each of the pairs and in the voltameter. These two orders of decomposition are equally the result of the affinity for oxygen of the positive metal of the pair. If this affinity is very powerful, as that of potassium or of sodium, a single pair,— amalgam of potassium, and water acidulated with sulphuric acid,— is sufficient to decompose the acidulated water of the pair, and the same water placed between two platinum electrodes;

indeed, affinity, according to the arrangement of the circuit, can be exercised only so long as the liquid of the pair, and that of the voltameter are both decomposed. If it is less powerful, as is the case when, instead of potassium, we have zinc, then we must add to that, which is exercised by one pair, that of a second or of a third, in order to decompose the liquid of the voltameter. If we suppose, therefore, what appears from all the experiments probable, that in a pair wherein there is only one active metal, the electro-motive force is proportional to the affinity of this metal, for one of the elements of the electrolytic liquid of the pair *, we shall have in the number of pairs necessary for overcoming a given affinity (that of the oxygen and hydrogen of a water, always acidulated to a same degree,) a very exact expression of the force of affinity.

It is to be remarked that the voltaic combination must always be of such a nature that, when the two metals of the pair are united by a metallic conductor, the liquid by which they are separated, is decomposed by the affinity of one of its elements for one of the metals; otherwise we should in vain add any number to each other, we should never obtain either current or decomposition of water in the voltameter. It is important that the liquid, with which the voltameter is charged, shall be always entirely the same; for if it changed in such a manner as to be more or less easy of decomposition, we understand that the comparison between the different voltaic combinations in respect to electro-motive force, and consequently to affinity, would be impossible. It is necessary also that in the pairs themselves, one of the metals should always be inactive; for otherwise the results would become complex. Thus, with pairs,—copper and zinc in diluted sulphuric acid, — we should have the measure, not of the affinity of oxygen for zinc, but of the difference between the affinity of oxygen for zinc, and that of oxygen for copper. With pairs of platinum covered with peroxide of lead and zinc in diluted sulphuric acid, we should have the means of the sum of the

* We must not forget, indeed, that the electro-motive force of a voltaic combination, is proportional to the number of pairs, that are formed with this combination.

affinity of oxygen for zinc and of hydrogen, for the oxygen of the peroxide.

Mr. Cooke has endeavoured to apply the method that we have just been explaining; only, he measured the electromotive force of each voltaic combination, by placing in the circuit of which it formed part, a tube filled with sulphate of copper, the liquid column of which might be lengthened or shortened so as, by means of this variable resistance, to cause each combination to produce the same effect upon a galvanometer, placed in the same circuit. The electromotive force, and consequently the affinity, was deduced from the comparison of the lengths of the liquid column in each case, according to Ohm's laws. Mr. Cooke, on taking various precautions in order to take account of the polarisation of the plate of platinum of the pair, has obtained the following numbers for the expression of the relative force of affinity of the various metals for oxygen in rain water, taking for unity the electro-motive force of a zinc-copper pair in the same rain-water, — a force which represents the difference between the affinities of the zinc, and of copper for oxygen: —

Zinc-copper	= 1
Potassium	3·13
Sodium	2·91
Zinc	2·23
Iron	1·85
Tin	1·75
Lead	1·70
Bismuth	1·29
Antimony	1·29
Copper	1·25
Silver	0·83

Mr. Cooke has likewise found for the expression of the affinity of oxygen for hydrogen, the number 2·36; we may be astonished that this number is higher than that, which expresses the affinity of oxygen for zinc; and that nevertheless zinc decomposes water. But we must remark that perfectly pure zinc does not decompose distilled water deprived of oxygen: and that consequently Mr. Cooke's results is not in

opposition to that, which results from the examination of the chemical reactions of zinc upon water.

We should not however attach too great confidence to the numbers found by Mr. Cooke, although the order in which the metals are arranged appears to us to represent well their degree of affinity for oxygen; while still believing the principle true, upon which his method is founded, there are yet many points to be made clear and data to be determined, before our being able to deduce from the numbers, that express in a tolerably exact manner, the relations of affinity of the different bodies in respect to each other.

One of the most essential among these points is to know in what condition it is necessary that the chemical action be exercised, in order to their being productive of electricity. When water is decomposed by the action of zinc, two phenomena are brought about, one the decomposition of the water itself, the other the oxidation of the zinc. Now, some philosophers, and M. Matteucci among others, pretend it is in the former of these phenomena only that there is liberation of electricity, and not in the latter. He relates that Davy had never been able to obtain the least sign of electricity, on causing iron or carbon to burn in very dry oxygen: he has himself proved the accuracy of this negative result, both in his experiments upon the electricity liberated in combustion of which we have spoken*, as well as in burning iron and zinc in oxygen, as in combining different metals with gaseous chlorine. He did not obtain in either case electric effects. He has moreover found that on causing chlorine, bromine, or iodine, to act directly upon the positive metal of a pair, zinc for example, plunged in a liquid, separated by a porous diaphragm from the liquid, in which the negative metal is plunged, the force of the current is in no way increased, although the zinc is attacked by the chlorine, bromine, or iodine. It is not the same as we know, if the chlorine, bromine, or iodine, is found in the liquid of the negative metal, because then the decomposition of the water is facilitated. In like manner as the combination of the two free

* Page 746. and the following pages.

elements does not produce electric signs, so also the decomposition of a binary compound, without their being a recombination of one of its elements, does not produce any, according to M. Matteucci. Thus, oxide, as well as bi-oxide of silver, peroxide of lead and chloride of gold, projected upon a platinum crucible powerfully heated and in communication with the condenser, have not produced electricity; neither the element that remained in the crucible, nor that which escaped from it, were found electrised. From these facts and others of the same kind, M. Matteucci had thought he might conclude that the combination of a simple metalloid body with a metal does not produce electricity, neither in the dynamic nor in the static state; that consequently in the pairs of the pile, the electric effect is due to the metalloid forming part of a combination before combining with one of the metals of the pair.

M. Becquerel does not share in M. Matteucci's manner of seeing it: he thinks that the results, negative in the case of the combustion of different bodies, is due to the circumstance, that the ambient medium being insulating, the electricities produced in chemical action cannot propagate themselves as they can when this medium is a liquid; and that they then recombine in proportion as they are developed, so that they are not perceptible. He has further shown that an iodide or a chloride solution increases the intensity of the current of a pair, as well when it is found in the compartment, in which the zinc of the pair is, as when it is placed in that where the copper is: the solutions tried, whether in the natural state, or in the iodide or chloride state, were a solution of nitrate of potash and a solution of potash. It does not appear to us, that these latter experiments invalidate M. Matteucci's conclusions; for nothing proves to us, that the iodine or the chlorine of the solutions acts directly upon the zinc; it rather appears to us probable that they facilitate its oxidation by aiding the decomposition of the water of the solutions.

The point upon which M. Becquerel seems to me to be right, is when he affirms that the simple combination of an

oxide and an acid produces electricity, as he has proved in his numerous experiments upon the mutual action of two solutions separated from each other by a porous membrane, and in particular in his very remarkable pair, potash and nitric acid. We know, indeed, and we have proved, that we must not go and seek for the cause of the electricity, that is developed, elsewhere than in the chemical action of the two solutions upon each other, we ought even to add that this action contributes to the liberation of electricity in the two-liquid piles. Thus, there is no doubt that, when we have a pair, —zinc, sulphate of zinc, and copper, sulphate of copper,— the mutual action of the two sulphates separated from each other by the porous diaphragm, does contribute to the total effect. If we have not taken this into consideration, it is because we have taken the effect of the pair in its totality, and because also the electricity developed in this action is feeble, comparatively to that, which results from the oxidation of the zinc by the decomposition of the water.

Admitting therefore that the combination of an oxide with an acid produces electricity, we do not however see in this fact an objection against Matteucci's principle. Indeed, this combination is perhaps brought about in a less simple manner than is supposed; for my own part, I am disposed to believe that it is preceded or accompanied by a decomposition. We know in fact that, in the decomposition of salts, the element that goes to the negative electrode is not the oxide, but the metal of the oxide, sodium, for example, if a salt of soda is in question; and that the element which goes to the positive electrode, is not the acid alone, but a compound of the acid, and the oxygen of the base. Now, this proves to us that very probably in the combination of an acid and a base, there is a decomposition, perhaps of the base, perhaps of the water of the solution, the oxygen of which is carried to the acid, whilst its hydrogen takes possession of the oxygen of the base, whose metal combines with the oxygenated acid. In this action a phenomenon must take place analogous to that which occurs in the formation of chlorides by the action of hydro-chloric acid upon the oxides;

for it is very evident, that in electrolytic decompositions, all salts behave like chlorides in which the chlorine is replaced by an *oxysulphion*, if the acid is a sulphuric acid; or by similar compounds, if other acids are in question.*

We may add, that as a result of fresh researches in which M. Becquerel, by means of his depolarising apparatus, of which we have spoken above, has been able to guard against the causes of errors arising from the secondary polarities of the metals that are used as electrodes in the solutions, he has arrived at some general results upon the electricity produced in chemical actions, which confirm those that he had already obtained, and which we have already stated in our preceding paragraphs; he agrees with Matteucci on the point that, in the combination of a metal with dry oxygen, chlorine, iodine, and bromine, there is no production of electricity, which he attributes to the non-conductibility of one of the two bodies present; however, he admits that combustion developes electricity, and that the combustible body liberates negative electricity, whilst the burners liberate positive; yet, in this case, one of the bodies, the burner, is not a conductor. Finally, he observes, that water in its combination with the acids, comports itself as a base, that is to say, acquires negative electricity, whilst with bases it comports itself as an acid, and acquires positive electricity.

In fine, the question upon which we are engaged, of knowing in what case chemical action developes electricity, cannot be solved until we shall be better acquainted with the manner in which chemical action itself is brought about and when we shall know how to measure it; moreover, it is probable that the two questions are so connected, that one can only be solved at the same time as the other. A fact, which proves to us the state of ignorance in which we still are as to the manner itself, in which chemical actions are brought about, is that which relates to one of the most simple actions, namely, that of the simple oxidation of metals in atmospheric air. According to M. Bonsdorff, no metal oxidises in air perfectly dry, and deprived of carbonic

* It is proved by the example of the cyanides that compound bodies may play exactly the same part as chlorine, iodine, or bromine.

acid, not even potassium and sodium; he goes so far as to affirm that in air moist, but well deprived of carbonic acid, not any of the known metals oxidise, save arsenic and lead. However this may be, the former of these two facts, which appears to us well established, shows therefore that the oxidation of a metal in the air is not the simple result of the direct combination of this metal with oxygen; a more complex phenomenon takes place here, namely, a voltaic action, the metal decomposing the water by a local voltaic action, aided by the presence of the dissolved oxygen, which acts upon the hydrogen of this water; the presence of carbonic acid facilitates the action, by rendering the water more conducteous. We will not contest that with the aid of heat, there may not be, in some cases, direct combination of oxygen with the metal; but these cases, which are exceptional, do not prevent the oxidation being ordinarily, brought about as we have been explaining

Another important point in electro-chemical phenomena, upon which philosophers are not agreed, is to know whether compound bodies are able to propagate electricity without decomposing, in the manner of simple elementary bodies, such as the metals. We have already discussed the question, both in reference to the experiments upon which is founded the law of electro-chemical equivalents*, as well as incidentally in showing that we have never been able to observe any transmission of an electric current through water, without the electrodes being polarised, — a proof that the water is decomposed; and we have had the opportunity of giving an explanation of the numerous and ingenious experiments, by which M. Foucault had thought he was able to establish this physical conductibility of liquids. We think therefore, that, in the present state of the science, and in face of the known facts, we are compelled to admit that the molecular propagation of electricity in liquid bodies cannot be brought about without being accompanied, in compound liquids, with electrolytic decomposition. We shall not contest that pro-

* Vol. II. pp. 424. 677. and 701.

pagation may take place in a liquid, especially if it is a bad conductor, by a discharge between the electrodes, analogous to that which constitutes the electric spark or the voltaic arc, and in which the liquid plays only a passive part,— that of an obstacle to the establishment of this discharge; it then frequently happens that the liquid itself is decomposed by the heat of the spark; but this fact is in no degree in opposition to the principle that, when the propagation takes place molecularly, there is electrolytic decomposition of the liquid.

Among the numerous questions which are still to be solved on the subject, upon which we are occupied, one of the most important would be to know what the relation is that connects the force of affinity with the electric effect, that is generated by the action of this force. Some attempts have been made in this respect: we have made allusion to it in the section commencing at p. 783.; we think we ought to dwell upon it for one moment longer, although its result is very uncertain and very limited; for it only concerns the affinity of oxygen and hydrogen. We have already seen that Wheatstone and Pouillet had succeeded in comparing the current, which results from the decomposition of a certain quantity of water, with that which is produced by a thermo-electric pair of a given power; but their result, although demonstrating the great superiority of the electro-chemical current over the thermo-electric current, gave no idea of the absolute quantity of the electricity liberated for the production of the former. Faraday and Becquerel have successively endeavoured to obtain the value of this quantity.

Faraday observed that the current, necessary for decomposing a grain of acidulated water, is sufficient for maintaining at a red heat, during the same time that he employed for decomposing the water, namely 3 minutes, 45 seconds, a platinum wire of $\frac{1}{100}$th of an inch in diameter. Now, he estimates that the quantity of electricity, which it would be necessary to employ, in order to produce the same effect, would be that furnished by 800,000 charges of a battery of Leyden jars, composed of 8 jars, of 8 inches in height, and $7\frac{1}{2}$ inches in diameter, charged with 30 turns of the

plate of a powerful electrical machine. If such is the expression of the quantity of electricity equivalent to that which is necessary for decomposing a grain of water, this expression is also that of the quantity of electricity, that is liberated by the combination of the quantities of oxygen and hydrogen necessary for producing a grain of water;—an enormous quantity, as we see.

M. Becquerel has found, by an entirely different method, a result that is not very far removed from that of Faraday. He first determined the force of the current, that is developed by the secondary polarities engendered upon plates of gold, which serve as electrodes in distilled water to discharges of Leyden jars; he has found that, for discharges which are not very considerable, the current, and consequently the polarities, which give rise to it, are proportional to the explosive distance, and consequently to the quantity of electricity, that passes in the water, in which the gold plates are plunged. Then, he determined the secondary polarities on the same gold plates both in distilled water, by means of a current arising from a very feeble pair formed of an amalgam of zinc placed in a porous tube, and of a platinum wire plunged in distilled water. He satisfied himself that the polarities acquired are proportional to the time, during which the current is transmitted, provided this time is very short. Thus, for a duration of 1″ he found that the polarised plates gave a current of 10°·73, and, for a duration of 0″·5, a current of 5°·33, that is to say, one-half less powerful. In order to compare the electricity of the discharge with that of the current, he commenced by determining with care the intensity of the current, due to the polarities produced by the discharges; and he found that this current produced upon the galvanometer a mean deviation of 17°·97. He then substituted the current of the pair for the discharge of the battery, and he found that this current in passing for 1″ brought about a polarity upon the plates, producing 16°·50 of deviation. Setting out from the principle, that the polarities or the chemical actions, by which they have been produced, are proportional to the quantities of electricity in motion, he deduced from it, that the quantity of electricity formed in 1″ by the pair, is to that of the dis-

charge as 16·50 : 17·97 or as 0·92 : 1. Now, by a succession of delicate experiments, M. Becquerel succeeded in determining to how much decomposed water the current of the pair acting for 1″ corresponded; he thus succeeded in finding that, in order to decompose a gramme (15·43 grs.) of water, a quantity of electricity was required, equivalent to what would be furnished by 51,586,400 discharges of a battery having one square metre (1·9609 yards.) of surface. This number is reduced to 20,063,456 when the charge of the battery is at its maximum. On reducing Faraday's result to the same conditions, we find 21,850,451. The difference is very inconsiderable for experiments of this nature. We may therefore conclude from this, adopting the round number of 20,000,000 for one gramme, that in order to decompose a milligramme (·0154 grs.) of water, there are required 20,000 discharges of a battery, presenting a surface of one square metre, or the discharge of an electric pane, that would have a surface of about five acres. Now, it is this same quantity of electricity, that must be produced by the decomposition of this same milligramme of water, brought about by chemical means; and, if it were accumulated, so as to discharge itself instantaneously, and not in a successive manner in proportion to its production, it would be capable of producing the effects of a flash of lightning. It is not necessary to attach too great an importance to the numerical values found by Faraday and Becquerel; but there follows from their researches an important result confirmed by Peltier, — namely how very small is the quantity of chemical action necessary for the production of a great electric power.

But of all the relations, by which chemical affinity is connected with the electricity that it generates, the most important is that which is established between the two forms of the same force, by the production of the heat which accompanies them. We have already made mention of the researches of Mr. Joule and of those of M. Favre, on this subject; and I have also quoted the experiment, by which I had succeeded in demonstrating the equality, that exists between the quantity of heat generated directly by chemical

action and that which is produced by the current to which this same chemical action gives rise.* We are now able to return with more details to this class of phenomena, which we had discussed only incidentally, being unable to investigate them deeply, before we had been occupied with electro-chemical actions.

Mr. Joule, after having established, as we have seen, the laws of the liberation of heat, by the passage of the electric current through liquids, had been led to admit that the heat developed by chemical reactions, without electricity being collected, is the same as that, which is produced by these reactions under the form of electric current, so that the heat in both cases would be due to the resistance to electric conductibility. The learned English philosopher has first proved that the quantities of heat, liberated by the combustion of the equivalent of bodies, are proportional to their affinities for gaseous oxygen: he arrived at this result, by seeking for the measure of these affinities in the action of the electric current, and by taking account of the modifications produced in its intensity, by the physical state of the elements of the combinations, that are formed in the pairs whence the current is derived. He has determined for potassium, zinc, iron, copper and hydrogen, the heat produced by the direct combination of these bodies in gaseous oxygen, according to a process analogous to that of Dulong; he then estimated the heat produced by the oxidation of the same substances in the production of the voltaic current; he thus finds the following numbers as expression of the degrees which one equivalent of each body raises, by its oxidation, the temperature of one pound of water, in the case of direct combustion, and in that of the oxidation with electricity collected.

	Direct Oxidation.	Voltaic Oxidation.	Voltaic Oxidation corrected.
Potassium - - -	17°·60	21°·17	
Zinc - - - -	11 ·03	13 ·83	11°·01
Iron - - - -	9 ·48	12 ·36	8 ·06
Copper - - -	5 ·18	9 ·97	5 ·97
Hydrogen - - -	8 ·36	10 ·47	10 ·40

* Vol. II. p. 250., and following page.

In order to obtain the corrected results contained in the third column, Mr. Joule remarks that, in oxidation by the moist way, which is accompanied by the production of a voltaic current, there are three forces, namely; the affinity of oxygen for the base of the oxide; that of the oxide for sulphuric acid (supposing that it is in a solution of sulphuric acid that the oxidation takes place); and finally, that of the water for the sulphuric acid; by eliminating the last two forces, which may be estimated directly, the numbers contained in the third column are found, which very nearly approximate to those of the first, except for iron, and for hydrogen, which is due to causes easily appreciable.

M. Favre, as we have already remarked, when occupied with the calorific effects of electricity, has established, by numerous and exact experiments, the truth of the principle, that I had advanced, on founding it upon a single experiment, and to which Mr. Joule had also arrived by another method; namely, that the heat, confined in the liquid of the pair, and that which arises from the resistance of the metallic circuit, whatever it may be, are always complementary to each other. M. Favre has further demonstrated, what Mr. Joule had only glanced at, that we always find in the liquid of the pair, and in the interpolar arc the sum total of the heat, which the chemical action put into play in this pair, would alone be capable of developing. We are unable to reproduce in detail the experiments of M. Favre; we shall merely call to mind that they were made according to the same method which was employed both by himself and by M. Silbermann in their great work on the measure of the quantities of heat liberated in chemical actions, and with a similar mercury calorimeter, but constructed upon a larger scale than the former. M. Favre has first measured the quantity of heat liberated in the pair, when the circuit was formed by a copper wire sufficiently thick for there being no appreciable calorific effect developed in consequence of resistance to conductibility: a wire about a twelfth of an inch in diameter and about a foot at most in length fulfilled the desired condition. He then substi-

tuted for this wire platinum wires of variable diameters and lengths, susceptible of being more or less heated; and by combining his apparatus so that the total heat, as well that of the wire as that of the pair, might be received by the calorimeter, he obtained with these variable wires, for the measure of the total quantity of heat, numbers very little different from each other, and the mean of which is 18,124 units of heat. The number obtained with the copper wire, which was not heated, is 18,137; this number represents the quantity of heat liberated by the chemical action corresponding to the liberation of 15·43 grains of hydrogen, or to the equivalent of 509·19 grs. of zinc dissolved, with transmission of electricity through a wire, which offers no resistance to the current. From the experiments made by M. Favre in common with M. Silbermann, the number that expresses the heat, liberated by the formation of sulphate of zinc without electricity transmitted, is 18,444, which, although slightly greater, yet approaches sufficiently near to the other two to enable us to conclude from it the accuracy of the principle that we have laid down.

M. Favre remarks with justice, that the law, which he has established, enables us to demonstrate that it is not the oxidation alone of the metal, that developes the current in a voltaic pair, but that the solution of the formed oxide in the acid contributes also to this production. Indeed, if we admit that the quantity of heat, which is produced in virtue of chemical actions in a voltaic pair,—zinc and platinum plunged in a solution of sulphuric acid,—is represented by A + B − D, A being the heat liberated by the formation of an equivalent of anhydrous oxide of zinc, B the heat liberated by the combination of this oxide with the diluted sulphuric acid, and D the calorific equivalent of the water, namely, the heat absorbed by the decomposition of an equivalent of water, and consequently liberated by its formation; we shall have, according to the direct experiments of MM. Favre and Silbermann, A = 42,451; B = 10,455 and D = 34,462; whence A + B − D = 18,444, a number very near to 18,137, the veritable

heat liberated. If we admit that this heat is equal to only A — D, we have 7,989, a very different number from 18,137. It is therefore very evident that the oxidation alone of the zinc is not sufficient to account for the effects generated by the current.

It is by setting out from considerations of the same kind that M. Favre seeks to explain, why we are unable to decompose water in a voltameter, when we arrange but one single pair, — zinc and platinum plunged in water acidulated by sulphuric acid, — whilst this decomposition is able to take place with a single Grove's pair, in which the platinum is surrounded with nitric acid. He remarks that the heat, necessary for establishing hydrogen in the free state in the voltameter, that is to say, for decomposing water, is not found in the chemical reactions that take place in the former pair, whilst it is found in those which take place in the latter. In fact, in the former pair this quantity of heat is A + B — D = 18,444 units, as we have seen; whilst the decomposition of water absorbs 34,462. In the latter pair, there is no liberation of hydrogen; consequently there no necessity of deducting D from A + B, which causes that the liberated heat must be 52,906 units; but it is in reality only 46,021, because the chemical segregation of the oxygen from the nitric acid absorbs 6,885 units of heat by equivalent, which are taken from the heat liberated by the sulphatation of the zinc, and which must consequently be deducted from 52,906. But in all cases 46,021 greatly exceeds 34,462, — the number of units of heat necessary to the decomposition of water in the voltameter.

As we see, M. Favre sets out from the principle that the voltaic heat is merely a borrowing made from the heat liberated in the chemical action that produces the current: that consequently, in a closed circuit the total quantity of heat is constant for a same quantity of chemical action; and that, by distributing itself in different manners, according to the nature of the circuit, it suffers a simple displacement. The learned French philosopher is thus led to admit an instan-

taneous transport of heat, in the *latent state* it is true, which is able to traverse a conductor without raising its temperature, —a transport, which is made from molecule to molecule in the water placed in the circuit, in proportion as the successive molecules are decomposed and recomposed by the exchange which is made between them of the gaseous elements of which they are constituted. He estimates that we may thus better account for the effects, that are observed in electro-chemical decompositions, and consequently for the theory of the pile; but, still being led to believe that we may include the effects produced by the currents of the pile under two orders of manifestation, the former of which might be considered as due to *currents of latent heat*, and the latter to *currents of transmitted affinity*, he recognised that they arise, as well as the electricity itself, from the same source, namely, from chemical action.

Still admitting, with M. Favre, the intimate connection that exists between the quantities of heat liberated in the different parts of a circuit, we cannot consider them as simple displacements of that which is produced in the pair; we are rather disposed to attribute them to the distribution, variable with the nature of the circuit, of the force which arises from the exercise of affinity in the pair. But, before developing our thought, we ought, in order to complete the exposition of the subject on which we are occupied, to say a few words upon the more recent researches of M. J. Regnault which appear to us to accord with the opinion of M. Favre.

M. J. Regnault, setting out from an experiment, by which M. Favre finds that the heat liberated by the oxidation of the equivalent of amalgamated zinc, is superior by 352-units to that which is liberated by the oxidation of the equivalent of pure zinc, concludes from it that this difference is due to the fact that in the amalgam, the zinc being liquid, it is not obliged, as when it is solid, to absorb heat in its transformation into sulphate,—an absorption which diminishes, in the same degree, that which is produced by chemical combination. The 352 units represent then the quantity of heat become

latent in amalgamated zinc; and which is found again under the form of electricity in the excess of electromotive force, that is presented by amalgamated zinc over pure zinc. This transformation of heat into electro-motive force does not seem to us necessary in order to explain the influence of the amalgamation, which appears to us to be simply due to the fact that affinity is more easily exercised between the acidulated water and the zinc, when the latter is dissolved; since there is no longer any cohesion to overcome,—a similar phenomenon to that which is presented by the greater proportion of chemical actions. The same cause, namely, the more easy exercise of affinity, appears to us equally to explain the greater development of heat, that accompanies the oxidation of zinc, when, instead of being solid, it is amalgamated.

Moreover we shall not contest that the liberated heat and the electro-motive force march together, without being altogether the cause, each of the other; since they appear to us equally to depend, with regard to their intensity, upon that of the affinity, which gives rise to them both. M. J. Regnault remarks, in fact, that the relation between the heats liberated in a Grove's pair and in a Daniell's pair, is the same as that of the electro-motive forces of these two pairs, namely, is equal to about 1·731. Mr. Wood, as the result of experiments upon the heat, liberated by the oxidation in water of different metals, had previous to this found that the order of these metals, classed according to the quantity of heat to which their oxidation gives rise, is exactly the same as that which is furnished by the comparison of the electro-motive forces that arise from their combination with oxygen. However, the question upon which we are occupied, would require still further researches in order to its being completely solved.

However it may be, it appears to us to be well demonstrated that there is an intimate relation between chemical affinity on the one hand, and the heat, as well as the electricity that it liberates on the other hand; and that it is in the determination of the quantities of heat developed and the electro-motive forces generated, that we shall be able to find the

most exact measure of affinities. It is not until such a work as this shall have been accomplished, that it will be possible to found upon bases in any degree solid an electro-chemical theory. However, I shall endeavour for the present to put forth briefly upon this point certain ideas, which appear to be more in accordance with the facts actually established, than the hypothesis, with which we have hitherto been contented, still recognising that it is impossible, in the present state of science, to give a completely satisfactory theory.

We have already called attention to the two electro-chemical theories, that have been proposed, one by Berzelius, the other by Ampère*; —the former based upon the hypothesis that all atoms have two electric poles of a contrary nature; the latter, on the hypothesis that all atoms have a natural electricity, some positive, others negative. We have observed that the latter theory possesses the grave inconvenience of dividing bodies into two distinct categories, the one electro-positive, the other, electro-negative; whilst it is evident that their electric property has nothing absolute, since the same body plays sometimes the part of electro-positive, sometimes that of electro-negative, according to the body with which it is combined. This objection is with us an objection of principle, to which it is impossible to reply, notwithstanding the ingenious artifices, by means of which endeavours have been made to refute it. The former theory, that of Berzelius, appears to us to present less objections in its principle, than in the manner, in which its author regards it in its details, and makes application of it. We have already demonstrated all the improbability that is presented by the hypothesis of Berzelius, that the atoms, while having two electric poles, become unipolar as soon as they combine, namely, that they retain only one of their electricities on combining, and abandon the other. We are moreover about to see that this hypothesis is not necessary in order to explain electro-chemical phenomena, which may be very well reconciled with the existence of a permanent polarity of the atoms. We have

* Vol. II. p. 48.

already sought to explain, by means of this polarity, magnetic and diamagnetic phenomena; we are now about to endeavour to show that it accounts also very well for electrochemical phenomena.

The principle from which we set out is,—that every atom has two electric poles, contrary, but of the same force; is it to a movement of rotation upon itself, or to another cause, that this polarity is due? This is of little importance; it is with us a primitive fact. One atom differs from another atom, with regard to its polarity, only inasmuch as one of them has a more powerful polarity than the other, but, in the same atom, the two electric poles are always of the same force. When two insulated atoms are brought near to each other, they attract each other by their opposite poles; but, as they are spherical, they can come into contact only by one of the poles of the former, and by the contrary pole of the latter: will it be indifferently the positive or the negative pole of the former, that will come into contact with the negative or positive pole of the latter? We shall be obliged to admit a principle, which it appears to us is able to be founded upon a great number of facts: that is to say that, when the two atoms are free and insulated, it is always the positive pole of that which has the stronger polarity, that unites with the negative pole of that which has the more feeble polarity. If they have the same force of polarity, there is no reason why they should unite by two of their contrary poles, rather than by the other two. Then they are not attracted by their poles; but they simply obey the *molecular attraction*, due to the effect of their mass; this is the case of homogeneous atoms, the attraction of which constitutes cohesion; whilst, when the atoms are heterogeneous, they are attracted by their opposite poles, they then obey *chemical affinity*.

Chemical affinity is therefore the result of the attraction of two different atoms by their contrary poles; but it is exerted in such a manner, that the positive pole of the more powerfully polar is united with the negative pole of that which is less powerfully so. The compound atom, that results from

the union of the two elementary atoms, has equally two poles, that is to say, the negative of the more powerful atom, and the positive of the more feeble one; these two poles are equal, because the excess of the more powerful over the more feeble of those which are united, serves to neutralise a corresponding part of the electricity of the free pole of the more powerful; the compound atom is therefore found under the same conditions as the free atom, and enjoys the same properties. Thus, on supposing that oxygen is that one of the simple substances, which has the more powerful polarity, an atom of oxygen will unite with one of sulphur, so that its positive pole is adhering to the negative of the sulphur; it will be the same for the union of one atom of oxygen with two atoms of hydrogen. An atom of chlorine will unite with hydrogen in the same manner as oxygen; whilst it will unite with an atom of oxygen in such a manner, that it will be the positive pole of the oxygen, that will be united to the negative pole of chlorine; thus, it will be by its positive pole that chlorine will unite with hydrogen, and by its negative that it will unite with oxygen.

A compound atom, when it is insulated, has therefore, like the simple atom, two contrary and equal poles; the electricities of these two poles unite by the surface itself of this atom, in the same manner as we have admitted that it takes place for the simple atom.* But, if we place the compound atom between two contrary polarities, between the two poles of a pile for example, this atom is immediately so arranged that its + pole is turned on the negative side of the pile, and its − pole on the positive side of the same pile; when water therefore is the subject under consideration, it is the atoms of hydrogen, that are turned with their positive pole on the side of the negative pole of the pile, and the atoms of oxygen on the side of the positive pole. The polarisation of the molecules of electrolytic liquids, which always precedes their decomposition, is therefore a consequence of their natural polarity. Now, if the electric power is sufficient,

* *Vide* Vol. II. p. 49. *fig.* 177.

the positive electricity of the positive electrode attracts the free negative of the first molecule of water, and thus determines the separation of the oxygen, which abandons its hydrogen to the oxygen of the following molecules of water, and so on. The difference between the natural state of a liquid and its state of electric polarisation, consists therefore of this,—that, in the former state, the molecules left to themselves are in a complete electric equilibrium, the equal and contrary electricities with which their two poles are endowed, unite by their surface; whilst, in the latter state, the electric equilibrium is broken, the contrary electricities no longer uniting by the surface of the molecules, whose positive poles are all turned on the side of the negative of the pile, and the negative on the side of the positive of the pile. This state of polarisation is followed by electrolysis; that is to say, by the separation of the constituent atoms of each particle, and their combination with the contrary atoms of the following or the preceding particles, except for those of the extreme particles, which are liberated at the surface of the electrodes. Only we should remark that, at the moment when the atoms of oxygen and hydrogen of two consecutive particles become free, they must turn round, so that it is the + pole of the oxygen, that combines with the — pole of the hydrogen, and not the + pole of the hydrogen, that combines with the — pole of the oxygen; since this turning round and combination being once brought about, polarisation recommences.*

All electrolytic decompositions are explained in the same manner. We shall give a few examples only of them. Thus the molecules of a solution of sulphuric acid may be considered as formed of a molecule of sulphuric acid, the + pole of which has attracted the — pole of the molecule of water united with that of the acid; but the + pole of the molecule of sulphuric acid belongs to the sulphur, the — pole of the molecule of water belongs to the oxygen; so that, when the molecules of the solution are decomposed, after having been polarised, it is not astonishing that the atom of

* See for the necessity of this turning, p. 351. of Vol. II.

oxygen travels with the molecule of sulphuric acid, separating itself from the atoms of hydrogen, and forming what we have called an *oxy-sulphion*. It will be the same when, for the hydrogen is substituted a metallic base, such as sodium or copper, with the difference that, at the negative electrode sodium decomposes water, whilst copper is deposited there in the metallic state. The mode of the electrolytic decomposition of non-binary compounds, must depend upon the manner in which combination is brought about between the various atoms, that enter into their formation, and consequently upon the degree of affinity, or relative electric polarity of these divers atoms. It is therefore in studying the phenomena that accompany combination, and in particular in measuring the electro-motive force and the heat, that are developed in it, that we may be enabled to render an account of the manner in which these various atoms are grouped and are separated in decomposition. With regard to binary compounds, their decomposition is easily explained, in the same manner as that of water; thus, in that of hydrochloric acid, the chlorine comports itself as does oxygen when water is the subject in hand; it is the same with other chlorides, with sulphurets, with cyanurets, as with the oxides. In the decomposition of chloric, sulphuric acids, &c., chlorine, sulphur, &c., no longer comport themselves like oxygen, but like hydrogen. All these results are the evident consequences of our theory.

The formation of compounds is at first sight more difficult of explanation in this theory than their decomposition; not in the case of binary compounds, the elements of which being free combine according to the mode that we have described above; but in the case, in which the formation of one compound does not take place, except by the decomposition of another. However we then consider that the same theory may explain in a satisfactory manner what takes place.

In order to fix our ideas, let us suppose a plate of zinc, plunged into a solution of sulphuric acid; the first effect of the presence of the metal in the liquid should be to destroy the electric equilibrium of the particles of the solution in

contact with it *; hence the negative electricity of the oxygen and the positive of the hydrogen of each of these particles become free; but as the former is much more powerful than the latter, since oxygen is much more powerfully polar than hydrogen, it is it which acts upon the metal, by attracting the + pole of its particle, and by thus polarising it; in its turn the free positive electricity of the hydrogen of the particle of water acts upon the following molecule of the solution and polarises it, destroying also its electric equilibrium, so that its negative oxygen is turned on the side of the particle in contact with the zinc and so on. In this way is established that polar state, which we have admitted to be the first effect of the contact of a metal with the electrolytic liquid, and which must take place with every body that is a conductor of electricity, even when it is not followed by the chemical action that gives rise to a new compound. With regard to this chemical action, which consists in the decomposition of the liquid and the combina-

* The contact of a conducting body, must indeed prevent the recomposition of the free electricities of the combined atoms, which took place by the exterior surface of these atoms; it follows from this, that the atom of oxygen, which is combined, is thus found to have its negative electricity entirely free, whilst a part of its positive is disguised by the atom of hydrogen; on this account, it is that it comes and adheres to the metal by its negative pole. It is probable that the catalytic property of platinum and of some other substances is due to the same cause. When molecules of oxygen and hydrogen are in very intimate contact with platinum, the electricities of their respective poles cease to be recomposed by the surface itself of the atoms; the atoms of oxygen then adhere at their positive poles with the surface of the platinum; those of hydrogen adhere to it by their negative poles; and then the free poles of the atoms of oxygen and hydrogen are alternated, being of a contrary nature; hence results the combination of the atoms of these two gases, accompanied by a small electric discharge through the platinum, and a liberation of heat. The electricity that traverses the platinum, cannot be collected directly, on account of the infinitely small distance of the atoms, whose electricities are thus combined. The adhesion of gases to the surface of metals is probably due in great part indeed to their electric polarity; it is a phenomenon analogous to that of the polarisation that is exerted upon a molecule of a liquid by a metal plate that is plunged into it. We therefore conceive why, whether for obtaining a powerful adhesion, or for producing the catalytic effect, it is necessary that the metallic surface be very clean, and that if it is very much divided, its power is increased. We equally conceive why this surface must not itself combine powerfully with oxygen, since then the latter could no longer combine with the hydrogen; we say *powerfully*, because the adhesion of oxygen to platinum for example, is truly a chemical combination; since it is the result of electric polarity and not of simple molecular attraction; and we have an experimental proof that it is a combination in the fact of the disaggregation of the surface of platinum, which has been employed during a certain time for bringing about the combination of oxygen and hydrogen, by the effect of its catalytic power.

tion of one of its elements with the metal, it takes place generally, as we have seen, only when the electric chain can be formed, whether by the effect of a want of homogeneity in the metallic surface itself, or by the effect of its contact with another substance, constituting with it a voltaic pair. However, it may happen that with certain bodies, such as those whose polar state differs greatly from that of oxygen (very oxidisable metals), the chemical action, which follows the establishment of the polar state, may take place without the circuit being formed, as also with metals, that are very little oxidisable, it does not take place even when it is formed. We conceive that the explanation which we have been giving is easily applicable to all cases analogous to that which we have taken for an example, to those in particular, in which the solution is a chloride, a sulphuret, a cyanide, and not only a combination of oxygen, and in which the compounds formed are consequently in like manner chlorides, sulphurets, cyanurets, &c.

Thus, all chemical actions of the kind of those of which we have been speaking are electro-chemical actions, in all respects similar, save that they are local, to those which take place in a voltaic pair. It is not therefore astonishing that the quantity of heat, which accompanies their exercise, is exactly the same; that this exercise takes place in one or other of the two forms, when the quantity and nature of the chemical action are the same.*

* In speaking of the experiments of Faraday and of Becquerel, for determining the quantity of electricity that is liberated in a certain chemical action, such as the oxidation of zinc, we have said that Peltier had succeeded on his part, by a very different process, in showing how prodigious is the quantity of electricity, that is developed by the effect of the most feeble chemical action. Although M. Peltier's results are not perfectly in accordance with those of the two learned philosophers whom we have named, they nevertheless confirm the accuracy of the principle, that they have established. Indeed, according to M. Peltier, we require merely the oxidation of *one hundred and fifty-one billionièmes* of a milligramme of zinc ($0^{mgr}.000000151 = 0.000000000233$ grs. Troy) in order to produce a *dynamic* electricity, capable of causing the needle of a sensitive galvanometer to deviate 1°; and the oxidation of *the tenth of the two thousand one hundred and thirty-six quatrillionièmes* of a milligramme of zinc; ($0^{mgr}.000000000002136 = 0.000000000000003297$ grs. Troy) to produce a *static* electricity capable of causing the needle of M. Peltier's electrometer to diverge 1°.

Returning to the chemical action that two simple bodies, neither of which form part of any combination, exercise upon each other, it is necessary, in order to its being brought about, that the approximation between the atoms shall be sufficiently great for the + pole of the more powerfully polarised to attract the — pole of that, which is less so. Heat, by exalting polarity, is able to facilitate combination. In the case in which one of the simple bodies is oxygen, we conceive that its ozonisation, which appears to consist of disaggregating the molecules, gives to the atoms, by insulating them, all their polarity, and thus increases the oxidising power of this gas. We know likewise that the oxidising action is much facilitated by the presence of aqueous vapour; this fact, which is constant, is evidently due to the phenomena then becoming electro-chemical; the vapour of water is polarised by the metal, as water itself is; and the affinity of the oxygen for the hydrogen of the aqueous particles favours their electrolyzation, and consequently the oxidation of the metal, which takes place at the expense of the oxygen of these particles, whilst the gaseous oxygen re-forms water with their hydrogen.

There is no doubt that every chemical action, which is not a simple combination of two isolated elements, but in which there is at the same time decomposition and production of a new compound, is, as we have already remarked, a very complex phenomenon; and that the atoms of bodies are grouped in a manner very different from that, in which they were grouped before the action. These changes in their mode of grouping cannot be brought about without there being a great disturbance in their movement, which brings about the elevation of temperature, with which the production of chemical action is always accompanied. Now, this elevation is the more powerful, in proportion as the affinity, that determines the chemical action, is more energetic, and as, consequently, the disturbance is greater. The very intimate relation that unites the quantity of heat produced with the affinity on the one hand, and the affinity with the electro-motive force on the other hand,

is very favourable to the hypothesis by which, attributing affinity to the natural electric polarity of the atoms, we make the polarity depend on a movement of rotation of the atoms upon themselves. Indeed, in the mechanical theory of heat, temperature must depend upon the rapidity of this movement of rotation, which itself must influence the energy of electric polarity.

We shall not dwell for the present further upon this altogether theoretical subject, seeing that, in the present state of science, we are still in want of facts in sufficient numbers to justify or to invalidate our hypothesis. We shall not conceal the objections, that may be opposed to it, namely, in particular, the difficulty of conceiving that a simple difference in the electric polarity of the atoms is able to explain affinity; the necessity of admitting in this hypothesis that it is always the positive pole of the atom, whose polarity is the more powerful, that attracts the negative of that, whose polarity is the more feeble; and never the negative of the former, that attracts the positive of the latter, at least when they are free and not combined; finally, if the rotation of the atoms upon themselves is the cause of their polarity, and at the same time that of their temperature, how comes it that different atoms, having consequently a different polarity, or a different movement of rotation, may have the same temperature?

Still recognising the force of the objections, that we have been presenting, we are yet able to reply to them in part. First, it appears to us that the polarity of the atom, is one of the principles best established by the whole of the facts, which constitute the science of electricity; the phenomena of electro-dynamic and electro-static induction, those of thermo-electricity, whether in insulating bodies or in conducting bodies, the facts relative to the liberation of electricity by friction, are almost impossible of explanation, if we do not admit this principle. And the principle once admitted, we can conceive no other difference between two atoms in this respect, unless it is that one has a more powerful electric polarity than the other. Hence the very intimate connection, that exists between chemical affinity and electricity, leads

necessarily, in the exercise of the former, to cause it to play a part in the polarity of the atom. We conceive, however, that this polarity, and consequently the action that it exercises, may be modified by the mode of the aggregation of the atoms; by their degree of insulation, and by their temperature; but it is not the less very probable that it is the cause of the tendency of two atoms to combine chemically; a combination which, consisting in the neutralisation of the contrary electricities of the two poles, that come into contact, liberates at the same time the contrary electricities also of the two more distant poles. But, when once the combination has taken place, the compound atom has but two poles, as the simple atom had, as we have explained. Now, I grant it, the hypothesis that consists in laying down as a principle, that it is always by the positive pole of the more powerfully polar atom, and by the negative of that which is less so, that the attraction of the two atoms takes place, would have need of being proved. However, the greater expansive force of positive electricity, compared with that of negative at equal tensions, which is established by so great a number of phenomena, gives to our hypothesis a certain degree of probability. Moreover, I do not despair that we may succeed in demonstrating it more directly.

If ever, as I hope, I succeed in obtaining this demonstration as the result of the electro-chemical researches, in which I am at this moment engaged, and which must form the subject of a special work, I shall endeavour at the same time to insist more than I can here do upon the theoretical relations, that may also be established between heat and electrical and chemical effects. I shall then be able to reply to the last of the objections, that I have just now laid down. For the present, I shall confine myself to remarking that, in the mechanical theory of heat, regard must be had, not only to the greater or less velocity of the movement of rotation of the atom, but also to its mass; and that if, for a same atom, the quantity of heat increases with this velocity, it does not follow that for two atoms having different masses, a same velocity of rotation is necessary, in order to their

having the same temperature. And what is true for isolated atoms is more so for molecules, formed by the aggregation of a greater or less number of atoms, upon which the influence of the mass is much more sensible; since aggregation itself results from the attraction due to the mass of the atoms. This question, as it is easy to perceive, touches the most delicate points of analytic mechanics; and it is not until we shall have succeeded in formularising a good mechanical theory of heat, that we shall be able to solve it in a satisfactory manner.

To sum up: we consider that we may, in a general manner and without risk of hazarding too much, distinguish chemical affinity from physical or molecular attraction, by admitting that chemical affinity is the attraction of atoms, operating by their contrary electric poles which come into contact, so that two atoms make no more than a single one, the polarity of which is a function of the polarities of the elementary atoms, whilst physical attraction results from the mutual attractive action that the atoms exercise over each other in virtue of their masses. This last attraction is never able to produce contact; because from the action, that is exerted upon the ether, which envelopes the atom in rotation, arises a repulsive force, the intensity of which increases in proportion as the space, which separates the atoms, that are attracted, from each other, goes on diminishing. It is this repulsive force, that increases with the rapidity of the rotation of the atom, and consequently with its temperature.

The distinction, that we have been establishing between chemical affinity and physical attraction appears to us to have, among other advantages, that of well characterising the distinctive features of these two forms of attraction. In the former, there is always electricity liberated, and liberation of heat, as well as the formation of a compound, which has no longer any physical relation with its constituent elements: now this must result from the manner in which we suppose that affinity is exercised, and in particular from the fact that the compound atom, when once it is formed, acquires an electric polarity or a movement of rotation upon its axis,

which is proper to it, and which is no longer the movement of rotation of either one or the other of the constituent atoms. In the latter, that is to say, physical attraction, the atoms, in grouping themselves by virtue of the attraction of their masses, do not come into contact,—cannot consequently produce electrical effects; they retain their proper movement of rotation upon themselves, which constitute their individuality. There may even here be some liberation of heat by the effect of the approximation of the atoms, as there is absorption by the fact of their separation; but these are phenomena altogether physical, and which are connected with the mechanical work, that takes place in molecular action.

We shall not terminate this paragraph without quoting in support of the hypothesis of the polarity of atoms, a very recent experiment of M. Foucault's, who has succeeded, by giving a very rapid motion of rotation between the poles of a powerful electro-magnet to a metal body of a rounded form, in producing in this body a strong heat. This elevation of temperature very probably arises from the successive and very rapid displacements, that the particles of bodies in rotation undergo, by the effect of the influence of the electro-magnet,—displacements themselves due to the fact that, in virtue of their polarity, the atoms are grouped under this influence in directions parallel to those of the currents of the electro-magnet, so as to give rise to induction currents. Moreover, we shall have occasion, at the end of the Third Volume, to return to this subject in an Appendix, that we shall devote to the works that have recently been done on magnetism and on dia-magnetism; we shall then endeavour to complete the theory, that we have just been sketching out, and which we had already in part set forth in the present volume.*

* Vol. II. p. 49., and following pages.

List of the principal works relative to the subjects treated upon in this Chapter.

Oersted.—Electricity produced by chemical actions. *Ann. de Chim. et de Phys.* t. xxii. p. 358.

Becquerel.—Electric effects produced in chemical actions. *Ann. de Chim. et de Phys.* t. xxiii. p. 152., and 244.; t. xxiv. p. 192., and t. xxv. p. 405.; t. xxvi. p. 176.; t. xxvii. p. 5.—Electric effects in the contact of liquids and metals.

t. xxvii. p. 29.—Simultaneous static and dynamic effects, (B. and Ampère), t. xxviii. p. 16.—Electric effect of oxygenated water. t. xxxv. p. 113.; t. xli. p. 5.; t. lx. p. 164.—Electric effect in the contact of water and of some crystalline substances.—Pyro-electric currents. *Arch. des Sc. Phys.*, (*Bibl. Univ.*) t. xxvi. p. 173.—Electro-chemical theory. *Ann. de Chim. et de Phys.* (*New Series*) t. xxvii. p. 5.—Electricity in chemical actions. *Idem.* t. xlii. p. 385.—Quantity of electricity associated with particles. *Comptes rendus de l'Acad. des Sciences*, (March 1846,) and *Arch. des Sc. Phys.* (*Bibl. Univ.*), t. i. p. 291. See for the works of M. Becquerel, the *Ann. de Chim. et de Phys. passim*, and his two Treatises on Electricity.

Matteucci.—Interior chemical action of the pile equivalent to the exterior action. *Bibl. Univ.* t. lviii. (1835.) p. 23. and following pages.—Production of electricity by chemical action. *Ann. de Chim. et de Phys.* (*New Series*) t. xvi. p. 257.—Secondary polarities. *Bibl. Univ.* (1838), t. xvii. p. 378., and (1840) t. xxviii. p. 410.—Production of voltaic electricity. *Arch. de l'Electricité*, t. iv. p. 65.; *Arch. des Sc. Phys.* (*Bibl. Univ.*); t. xii. p. 142.; t. xvi. p. 319.—Electricity by combustion. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxvii. p. 235.

Karsten.—Electricity in the contact of metals and liquids. *Bibl. Univ.* (1836) t. v. p. 154.

Pouillet.—Electricity in combustion, &c. *Ann. de Chim. et de Phys.* t. xxxv. p. 401. and t. xxxvi. p. 5.—Theory of the pile. *Comptes rendus de l'Acad. des Sciences*, t. iv. p. 267.—Quantity of electricity by the oxidation of zinc. *Idem.* t. iv. p. 785. *Traité de Physique.*

Buff.—Electricity not due to evaporation. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxvi. p. 240.—Electricity by flame. *Idem.* t. xviii. p. 265., and t. xxvi. p. 335.—Electricity in the contact of liquids and metals. *Arch. de l'Electricité*, t. iii. p. 566.

De la Rive.—Chemical action, source of electricity. *Ann. de Chim. et de Phys.* t. xxxvii. p. 225.; t. xxxix. p. 297.; t. lxi. p. 38.; *Bibl. Univ.* (1836) t. iii. p. 375.; t. iv. p. 152. and 359.—Action of sulphuric acid upon zinc. *Ann. de Chim. et de Phys.* t. xliii. p. 425.—Chemical action of a single pair. *Arch. de l'Electricité*, t. iii. p. 175.—Electricity due to deoxidation. *Bibl. Univ.* (1836) t. i. p. 151.—Pile of rammed carbon. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxiv. p. 77.—See, for the works of M. De la Rive, on the chemical origin of voltaic electricity, the *Mémoires de la Soc. de Phys. et de Hist. Nat. de Genève*, t. iv. p. 285., t. vi. p. 149., and t. vii. p. 457.; the *Arch. de l'Electricité* (1840 to 1845), and the *Arch. des Sc. Phys.* (*Bibl. Univ.*)

Schoenbein.—Theory of the pile. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xiii. p. 192.—Secondary Polarities. *Bibl. Univ.* (1838) t. xviii. p. 166. 187. and 365.—Electro-chemical effects. *Idem.* (1839), t. xxiii. p. 189.—Passivity of iron, bismuth, &c. *Idem.* t. iii. p. 377.; t. v. p. 177. and 397.; t. ix. p. 41; *Arch. de l'Electricité*, t. xi. p. 267. 286. 509. and 513.—Oxy-hydrogen pile. *Idem.* t. iii. p. 69.; t. iv. p. 56.—Pile with electro-chemical effects. *Idem.* t. xxiii. (1339), p. 189.

Faraday.—Chemical origin of voltaic electricity. *Arch. de l'Electricité*, t. i. p. 93. and 142. Quantity of electricity in the decomposition of water. *Bibl. Univ.* t. lviii. (1835) p. 305.—Chemical theory of the pile. *Bibl. Univ.* (1835) t. lviii. p. 263.; *Bibl. Univ.* (1840) t. xxvii. p. 192.; *Philosophical Transactions of the Royal Society of London*; and *Phil. Mag. passim.*

Poggendorff.—Electro-motive forces; relations between electric action and chemical action. *Arch. de l'Electricité*, t. i. p. 168.; t. ii. p. 5. and 196.; t. iii. p. 117. 124. and 134.; t. iv. p. 285.; *Arch. des Sc. Phys.* t. iv. p. 399.—Force of a non-constant pile. *Ann. de Chim. et de Phys.* (*New Series*), t. vii. p. 87.—Laws of galvanic polarization. *Idem.* t. xx. p. 217. *Annalen der Physik und Chimie, passim.*

Gassiot.—Large water battery, and theory of the pile. *Arch. de l'Electricité* t. iv. p. 242. *Arch. des Sc. Phys.* t. iii. p. 41. *Philosophical Transactions of the Royal Society of London*, 1844.

Nobili.—Electricity produced by the chemical action of solutions. *Bibl. Univ.* (1829) t. xxxvii. p. 10.; t. lvi. (1834), p. 150.

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Fechner.—Becquerel's oxygen pile. *Ann. der Physik.* t. xlviii. p. 1.

Jacobi.—Idem. *Bibl. Univ.* (1838), t. xiv. p. 171.—Constants of the pile, *Arch. de l'Electricité*, t. ii. p. 575.—Recomposition of the gas in the voltameter. *Ann. de Chim. et de Phys.* (*New Series*), t. xxv. p. 215.

Gaugain.—Gaseous pairs. *Comptes Rendus de l'Acad. des Sciences*; (October, 1853) and *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxiv. p. 274. —Electricity in combustion. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxvi. p. 67. and 240.

Marianini.—Secondary piles. *Ann. de Chim. et de Phys.* t. xxxviii. p. 5.—Voltaic piles, *Idem.* t. xxxviii. p. 337. and 442.—*Idem.* t. xlv. p. 118.

Grove.—Gas pile. *Arch. de l'Electricité*, t. iii. p. 489.—Voltaic reaction. *Idem.* t. iv. p. 148. *Idem. Arch. des Sc. Phys.* (*Bibl. Univ.*) t. ii. p. 354.—Electricity of flame. *Idem.* t. xvii. p. 240. and t. xxv. p. 276. *Phil. Trans. of the Royal Society of London*; and *Phil. Mag. passim.*

Beetz.—Passive iron. *Arch. de l'Electricité*, t. iv. p. 509.—Electro-motive power of gases. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xii. p. 285.

Nicklès.—Passivity of cobalt and nickel. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxiv. p. 79.

E. Becquerel.—Electro-chemical properties of hydrogen. *Ann. de Chim. et de Phys.* (*New Series*) t. xxxvii. p. 385.—Influence of gases upon the electricity of contact. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. ii. p. 59.—Electric effects due to the movement of pairs. *Ann. de Chim. et de Phys.* (*New Series*) t. xliv. p. 401.

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Riess.—Electricity by combustion. *Arch. de l'Electricité*, t. v. p. 91.

Hankel.—Idem. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xvii. p. 5.

Viard.—Influence of oxygen on the pile. *Ann. de Chim. et de Phys.*, (*New Series*) t. xxxvi. p. 129. and t. xlii. p. 5.

Daniell.—Voltaic combinations. *Arch. de l'Electricité*, t. iii. p. 623.

Smee.—Platinised silver pile. *Bibl. Univ.* t. xxvii. (1840), p. 186. and p. 386.

Silliman.—Carbon pile. *Arch. de l'Electricité*, t. iii. p. 649.

Bunsen.—Voltaic pile and preparation of carbon. *Ann. de Chim. et de Phys.* (*New Series*) t. viii. p. 28.

Callan.—Idem.—*Arch. des Sc. Phys.* (*Bibl. Univ.*) t. vi. p. 47. *Idem.* t. xxix. p. 162.

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Goodmann.—Pile with potassium. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. ix. p. 305.

J. Regnault.—Electro-motive forces. *Ann. de Chim. et de Phys.* (*New Series*), t. xliv. p. 453.

Svanberg.—Polarising force of hydrogen. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. iv. p. 296.

Lenz and Saweljev.—Electro-motive power of gases. *Ann. de Chim. et de Phys.* (*New Series*) t. xx. p. 184.

Kohlrausch.—Relations between electro-motive force and tension. *Ann. de Chim. et de Phys.* (*New Series*) t. xli. p. 357.

Joule.—Voltaic combinations. *Arch. de l'Electricité*, t. iv. p. 269.—Electric origin of chemical heat. *Ann. de Chim. et de Phys.* (*New Series*) t. xvi. p. 474.

Volta.—Electricity of contact. *Ann. de Chim.* t. xxix. p. 91.; t. xl. p. 217. and t. xli. p. 3. 65. and 106.

Biot.—Idem. *Traité de Physique experimentale et mathematique.* Paris, 1816.

Peclet.—Idem. *Ann. de Chim. et de Phys.* (*New Series*), t. ii. p. 233.

Zamboni.—Dry piles. *Ann. de Chim. et de Phys.* t. ii. p. 190., and t. xxix. p. 198. *Bibl. Univ.* (1837) t. viii. p. 189.

Delezenne.—Idem. *Arch. de l'Electricité*, t. v. p. 67.

Cooke.—Affinity and electro-motive force. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xvii. p. 322

Favre.—Relations between heat, affinity and electro-motive force. *Ann. de Chim. et de Phys.* (*New Series*), t. xl. p. 193.

Wood.—Heat developed by oxidation. *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxii. p. 82.

Bonsdorff.—Oxidation in air. *Bibl. Univ.* t. xviii. (1838), p. 373.

Foucault.—Heat developed by magnetic influence upon a body in movement. *Comptes Rendus de l'Acad. des Sciences*, t. xli. p. 450. (17th Sept. 1855.)

NOTE X. (p. 69.)

THE following is a List of the principal works relative to the subjects treated on in the Second and Third Parts of this Treatise, which are contained in the First Volume; and in the Appendix at the commencement of the present Volume.

PART II.

Chap. V. (Vol. I. p. 124.)

1st. The memoirs of Mr. Faraday, on the induction of ordinary electricity, communicated to the Royal Society of London in 1837 and 1838. *Philosophical Transactions of the Royal Society of London*, 1838.

2nd. The memoirs of M. Matteucci on the polarisation of plates of mica, and on the propagation of electricity in solid bodies. *Bibliothèque Universelle, Arch. des Sc. Phys.*, Geneva, 1846, t. ii. p. 371. *Ann. de Chim. et de Phys.*, Paris, 1849, t. xxvii. p. 133.

PART III.

Chap. I. (Vol. I. p. 156.)

1st. *Scoresby.*—*Ann. de Chim. et de Phys.* (Paris, 1838) t. lxix. p.106

2nd. *Nobili.*—*Bibl. Univ. de Genève*, t. lvi. p. 82., and the following pages.

3rd. *Barlow.*—*Bibl. Univ.* t. xxxiv. p. 188.

Chap. II. (Vol. I. p. 211.)

Oersted.—*Ann. de Chim. et de Phys.* t. xiv. (1820) p. 417.; and *Bibl. Univ.* t. xiv. p. 274., and xv. p. 137.

Ampère.—*Ann. de. Chim. et de Phys.* t. xv. xvi. xviii. xx. xxii. xxvi. xxix. xxx. and xxxvii.; and *Bibl. Univ.* t. xvi. xvii. xix. xx. and xxvii. (Years 1820 to 1828.) *Theory of electro-dynamical phenomena*, 1 vol. in 4to. Paris, November, 1826.

G. De la Rive.—T. xvi. p. 201., xvii. p. 188., xviii. p. 269.

Davy.—*Ann. de Chim. et de Phys.* t. xxv. (1824) p. 64.; and *Bibl. Univ.* t. xxv. p. 98.

Faraday.—*Ann. de Chim. et de Phys.* t. xviii. (1821) p. 337.

Savary.—*Ann. de Chim. et de Phys.* t. xxii. (1823) p. 91., and xxiii. p. 413.

Marsh.—*Bibl. Univ.* t. xx. (1822) p. 258.

A. De la Rive. — *Bibl. Univ.* t. xxi. (1812) p. 29., and *Ann. de Chim. et de Phys.* t. xxi. p. 24.

Weber. — *Ann. der Physik*, t. lxxiii. (1848) p. 193.

Chap. III. (Vol. I. p. 278.)

Arago. — Magnetism by currents and electric discharges. *Ann. de Chim. et de Phys.* t. xv. (1820) pp. 82. 93 and 393.

Davy. — Magnetisation of a still needle. *Bibl. Univ.* t. xvii. p. 191.

Nobili. — Magnetisation by a flat spiral. *Bibl. Univ.* t. xxvii. p. 174.

Savary. — Magnetisation. *Ann. de Chim. et de Phys.* t. xxxiv. (1827) p. 5.

Abria. — Magnetisation by currents. *Ann. de Chim. et de Phys.* (3rd series) t. i. (1841) p. 385.

Delesse. — Magnetism of rocks. *Arch. des Sc. Phys.* t. x. p. 207.

Holl. — Magnetisation of soft iron by currents. *Ann. de Chim. et de Phys.* t. l. (1832) p. 32., and t. lvi. (1834) p. 222.

Alexandre. — Influence of heat upon magnetisation by currents. *Arch. de l'Elect.* t. iii. p. 658.

Froment. — Magnetic instrument with a vibrating plate. *Bibl. Univ., Arch. des Sc. Phys.* t. iv. p. 294.

Nicklès. — Construction of electro-magnets. *Ann. de Chim. et de Phys.* (3rd series) t. xxxvii. p. 399.

Page. — Sound produced by magnetisation. *Bibl. Univ.* (new series) t. ii. (1839) p. 398.

Delezenne — *Idem.* t. xvi. (1841) p. 406.

Liphaus and Quetelet. — Magnetisation of iron by currents. *Ann. de Chim. et de Phys.* t. l. (1832) p. 331.

Marrian. — Sound by magnetisation. *Arch. de l'Elect.* t. v. p. 195.

Beatson. — Sound by the transmitted current. *Idem.* t. v. p. 197.

Idem. — Expansion of iron by the passage of the current. *Bibl. Univ. Arch. des Sc. Phys.* t. ii. p. 113.

De la Rive. — Sounds produced in iron by magnetisation and transmitted currents; and molecular phenomena. *Ann. de Chim. et de Phys.* (3rd series) t. xvi. p. 93., and t. xxvi. p. 158. *Arch. de l'Elect.* t. v. p. 200. *Bibl. Univ., Arch. des Sc. Phys.* t. ix. pp. 193. and 265.

Wertheim. — Sounds produced by magnetisation and influence of molecular actions. *Ann. de Chim. et de Phys.* (3rd series) t. xxiii. p. 302. *Comptes Rendus de l'Acad. des Sc.* t. xxiii. p. 336.; and *Bibl. Univ., Arch. des Sc. Phys.* t. xxi. p. 223.

Guillemin. — Influence of magnetisation on soft iron. *Comptes Rendus des Sc. de l'Acad. des Sc.* (1846) t. xxii. p. 264.

Joule. — Influence of magnetisation on the dimensions of iron. *Bibl. Univ., Arch. des Sc. Phys.* t. iv. p. 398., and t. v. p. 51.

Grove. — Arrangement of particles by magnetisation, and heat produced *Bibl. Univ., Arch. des Sc. Phys.* t. x. p. 182., and t. xi. p. 210.

Maggi. — Influence of magnetisation upon the conductibility of iron for heat. *Bibl. Univ. Arch., des Sc. Phys.* t. xiv. p. 132.

Marianini. — Influence of molecular action upon magnetisation. *Ann. de Chim. et de Phys.* (3rd series) t. xiii. p. 237., and t. xvi. pp. 430. and 448.

Matteucci.—Magnetisation by the current. *Bibl. Univ., Arch. des Sc. Phys.* t. v. p. 55.

Wartmann.—Sounds produced by the electric current. *Bibl. Univ., Arch. des Sc. Phys.* t. i. p. 419.

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Schweiger.— Galvanometer-multiplier. *Bibl. Univ.* t. xvi. (1821) p. 197.

Nobili.— Idem. *Bibl. Univ.* t. xxix. (1825) p. 119., t. xxxvii. (1828.) p. 10.; *Ann. de Chim. et de Phys.* t. xliii. (1830) p. 146.

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Pouillet.— Sine and tangent-galvanometer. *Compte Rendu de l'Acad. des Sc.* t. xx. p. .; and *Traité de Phys. et de Météor.*

Poggendorff.—Comparable galvanometer. *Ann. der Physik*, t. lvii.; and *Ann. de Chim. et de Phys.* (3rd series) t. viii. (1843), p. 115.

Lenz.— Comparable galvanometer. *Ann. der Physik*, t. lix.

Weber.— Idem. *Idem.* t. lv.

Despretz.—Tangent-galvanometer or compass. *Compte Rendu de l'Acad. des Sc.* t. xxxv. p. 449.

Gaugain.—Tangent-galvanometer or compass. *Compte Rendu de l'Acad. des Sc.* t. xxxvi. p. 191.

Bravais.—*Ann. de Chim. et de Phys.* (3rd Series) t. xxxviii. (1853) p. 301.

Ritchie.— Torsion-galvanometer. *Bibl. Univ.* t. xlvi. (1831) p. 9.

Melloni.—Comparable galvanometers. *Ann. de Chim. et de Phys.* t. liii. (1833) p. 1.

Peltier.—Comparable galvanometers. *Ann. de Chim. et de Phys.* t. lxxi. (1839) p. 225.

Chap. V. (Vol. I. p. 347, and App. Vol. II. p. 1.)

Arago.—Magnetism by rotation. *Ann. de Chim. et de Phys.*, t. xxvii. (1825) p. 363., t. xxviii. (1825) p. 325.; and t. xxxii. (1827) p. 213.

Babbage and Herschel.—Idem. *Bibl. Univ.* t. xxix. (1825) p. 354.

Harris.—Idem. *Bibl. Univ.* t. xlvii. (1831) p. 134.

Christie.—Idem. *Bibl. Univ.* t. xxix (1825) p. 254.

Ampère and Colladon.—Idem. *Mém. de l'Acad. des Sc.* (1827), and *Bulletin de Ferrussac*, t. vi. (1826) p. 211.

Haldat.—Idem. *Ann. de Chim. et de Phys.* t. xxxix. (1828) p. 232., and t. lxvii. (1838) p. 203.

Barlow.—Idem. *Bibl. Univ.* t. xxxiv. (1827) p. 188.

Poisson.—Idem. *Ann. de Chim. et de Phys.* t. xxxii. (1826) p. 225.

Faraday.—Induction currents. *Philosophical Transactions of* 1832 *and* 1833 ; *Bibl. Univ.* t. xlix. (1832) p. 341., and lix. (1835) p. 128. ; *Ann. de Chim. et de Phys.* t. l. (1832) pp. 5. and 113., and t. li. (1831) p. 404.

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Pixii.—Magneto-electric machine. *Ann. de Chim. et de Phys.* (1832) p. 76

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Riess.—Idem. *Ann. de Chim. et de Phys.* t. lxxiv. (1840) p. 158.; *Arch. de l'Elect.*

Verdet.—Idem. *Ann. de Chim. et de Phys.* (new series) t. xxiv. p. 377.

Knochenhauer.—Idem. *Ann. de Chim. et de Phys.* (new series) t. xvii. p. 130.

Dove.—Various influences of induction. *Ann. de Chim. et de Phys.* (new series) t. iv. p. 336.; *Arch. de l'Elect.* t. ii. pp. 290. 315. and 338., t. iii. pp. 49. and 63., t. iv. p. 331.

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Weber. Unipolar induction and theory. *Arch. de l'Elect.* t. v. p. 441.; *Electro-dynamische Maasbestimmengen* (Leipsig, 1846).

Palmieri.—Induction by terrestrial magnetism. *Arch. de l'Elect.* t. iii. p. 341., t. iv. p. 172., and t. v. p. 181.; *Ann. de Chim. et de Phys.* (new series) t. viii. p. 503.

Abria.—Induction of various orders and by discharges. *Ann. de Chim. et de Phys.* (new series) t. iii. p. 5., and t. vii. p. 462.

Ampère.—Action of a current and a magnet. *Ann. de Chim. et de Phys.* t. xxxvii.—Induction currents. *Ann. de Chim. et de Phys.* t. xlviii. (1831) p. 405. (1828) p. 113.

Prévost, Professor.—Theory of the action of currents. *Bibl. Univ.* t. xxi. (1821) p. 178.

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Lallemand.—Attraction and repulsion of induced currents. *Ann. de Chim. et de Phys.* (new series) t. xxii. p. 19.

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E. Becquerel.—Action of magnetism upon all bodies. *Ann. de Chim. et de Phys.* (new series) t. xvii. p. 449., and t. xxviii. p. 253.

Plucker.—Determination of the magnetic and diamagnetic power of bodies —Magneto-crystalline phenomena. *Ann. de Chim. et de Phys.* t. xxix. (new series) p. 129.; *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xi. p. 196.; t. xviii. p. 146., and t. xix. p. 102.

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NOTES

RELATIVE TO

MATHEMATICAL DEVELOPMENTS.

OF

CERTAIN PARTICULAR POINTS.

NOTE A. (p. 69.)

Note relative to the Propagation of Electricity.

We have said that M. Kirchoff had endeavoured to determine the laws of the propagation of electricity in other cases than that of linear propagation, and in particular in that of a conducting plate. It is impossible for us to reproduce in this note M. Kirchoff's complete work; we shall content ourselves with explaining the course that he has pursued; and, with showing how, on setting out from the principles established by Ohm (principles which Ohm himself has applied to the linear propagation of electricity), he has succeeded in determining the stationary state, that is acquired by electric tensions at the different points of a conducting plate, placed in the circuit of a pile; and how the results deduced from these calculations have been enabled to be verified experimentally.

M. Kirchoff admits, according to Ohm, that if, between two elements infinitely near of a same linear conductor, there is a difference of tension (which is necessarily infinitely small), there constantly passes from one of these elements to the other a quantity of electricity proportional to the difference of the tensions, to the section of the conductor, to the co-efficient of conductibility, and inversely proportional to the distance of the two elements. These principles, which are the same as those that we have already

established for linear propagation, being once admitted, the following is M. Kirchoff's method of applying calculation to them.

The place of the points, at which the tension has a same determined value, forms in general a curve, which enjoys the property of being normal to each of its points in the direction, according to which the electricity is propagated; since it follows immediately from the principle laid down above, that there is no movement of electricity from one point to another of this curve. According to this, the corresponding strata of equal tension will lead with certainty to the complete knowledge of the propagation of electricity. Now, in order to arrive at the equations of these curves, we must first find the expression of the tension u, in any point of the plate in the function of the co-ordinates of this point; and the equation, that will be obtained, on making this function of the co-ordinates equal to a constant, will be the equation of one curve of equal tension for a determined tension; all the others will be obtained in the same manner, by causing the constant to vary.

We shall not follow M. Kirchoff into the calculations by means of which he determines the expression of the quantity of electricity that passes in the unit of time through any element of a curve; but we shall confine ourselves to remarking that, for this purpose he considers two curves of equal tension infinitely near, and on these curves two elements comprised between the same normals; the parallelopiped, that has for its base the rectangle comprised between the two elements and the two normals, and for its height the thickness of the plate, being capable of being assimilated to a linear conductor; since the electricity is propagated in it only parallel to the normals. He thus succeeded in finding the equation of curves of equal tension; and this equation showed him that these curves are curves, whose centres are situated on the line that joins the points A and A′ of the plate on which the two electrodes abut — in a situation such that the extremities of the diameter of each curve are situated harmonically in relation to the points A A′.

M. Kirchoff has verified the conclusions of theory by numerous experiments. He has first determined the form of the lines of equal tension on a circular plate, communicating by two points of its form with the electrodes of a pile. The plate was touched at the extremities with the wire of a galvanometer; and the relative positions were determined, which it was necessary to give to

these two extremities, in order to produce no deviation upon the needle of the galvanometer; in this case, the two points of contact belong to a curve of equal tension; and this curve had truly the form and the position that was assigned to it by theory. M. Kirchoff has also found a complete agreement between the numerical expression of electric tension, which he had succeeded in determining, and the results obtained at the end of a series of experiments, in which the difference of the tensions of two points taken on the plate, was neutralised by the electro-motive force of a thermo-electric pair, which served to measure this difference. Finally, M. Kirchoff has further verified the accuracy of his theory by measuring the deviations of a small magnetised needle, suspended at a very small distance above the various points of the disc still placed in the circuit, and by comparing them with those which he had succeeded in determining theoretically.*

NOTE B. (p. 86.)

Note relative to derived Currents.

We have defined what we understand by *primitive* current, *principal* current, *partial* current, and *derived* current. It remains for us to give their values, which are easily deduced from Ohm's laws. Calling the intensity of the primitive current I, that of the principal current I′, those of the partial and of the derived currents i and i'—the resistance or the reduced length of the portions of the circuit, corresponding to the principal, the partial, and the derived currents, L, l and l'; calling E the electro-motive force, and bearing in mind that the two circuits l and l' may be replaced by a single one, whose resistance is equal to $\frac{l\,l'}{l+l'}$ we shall have, as we demonstrated (p. 78.) $I' = i + i'$.

$$I' = \frac{E}{L + \frac{l\,l'}{l+l'}} = \frac{E\,(l+l')}{L(l+l') + l\,l'} \qquad I = \frac{E}{L+l}$$

Moreover, as the portions of rrents, that pass through two conductors, which abut at the same points of junction, are in the inverse ratio of the resistances of these conductors, we have

* A more complete idea may be formed of M. Kirchoff's researches, by consulting the detailed and very well arranged extracts, that M. Verdet has given of the theoretic calculations and labours of the learned German philosopher in the *Annales de Chim. et de Phys.* t. xl. pp. 115. and 327. There will be found also (t. xl. p. 236.) an extract of the researches of M. Smaasen on the same subject.

$i : i' = l' : l$; whence $i : i + i' = l' : l' + l$.

We deduce from this $i = \frac{(i+i')\,l'}{L + l'}$; and substituting for $i + i' = \imath'$, the value of $\imath'$, we have $i = \frac{E\,l'}{L\,(l+l') + ll'}$; and in like manner we have $i' = \frac{E\,l}{L\,(l+l') + ll'}$.

Mr. Wheatstone has applied the theory of derived currents to the construction of several apparatuses, the detailed description of which is found in the Memoir, published by the learned English philosopher in *The Philosophical Transactions of the Royal Society of London*, 2nd part, 1843. We shall confine ourselves here to stating summarily the object and the principle of the two most important of these instruments, having already made known the rheostat in the body of the work.

The object of the first instrument is to measure small resistances too feeble to be determined by the rheostat; and this by means of a differential apparatus. With this view, four similar conducting wires are arranged in a lozenge, the precaution being taken of providing a solution of continuity in the two, that are adjacent at one of the obtuse angles of the lozenge. The two electrodes are placed at the two acute angles, and the two extremities of a galvanometer at the two obtuse angles of the lozenge. If the four conducting wires were all continuous, as they are, and perfectly similar, there would be established in the wire of the galvanometer two currents, equal, but moving in contrary directions; so that the needle would remain at rest. If now, by filling up the solution of continuity of one of the wires, we introduce an unknown resistance, the current that traverses it, is more feeble than the other; and equilibrium is established by filling up the solution of continuity of the other wire by a known resistance, which is rendered equal to the unknown resistance, and which serves consequently as its measure. The partial current is thus rendered equal to the derived current.

The object of the second apparatus, to the construction of which Mr. Wheatstone has applied the properties of derived currents, is to determine with accuracy the deviation of the needle of the galvanometer, that corresponds to a current of an intensity, which is in a certain relation—the half, for example,—with that of the current, which has produced a given deviation. The following are the principles upon which the arrangement of the instrument rests. "If a wire of the same length, thickness, and

conductibility, as that of the galvanometer, be placed so as to divert a portion of the current from it, it is obvious that one-half of the current will pass through the galvanometer wire, and the other half through the diverting path. Though it simplifies the consideration to suppose the extra wire to have the same length, diameter, and conducting power, it is easy to see that the same result follows if the two wires present the same resistance, which they do whenever $s'c'l' = s\,c\,l'$. If the added wire produced no alteration in the intensity of the principal current, one-half of the former force would act upon the galvanometer; but this is not the case, the addition of the wire produces the same effect as doubling the section of the galvanometer wire would do, and the total resistance of the circuit is therefore diminished. If the strength of the original current, when it passes wholly through the galvanometer $= \frac{E}{R+r}$ (r being the resistance of the galvanometer wire, and R all the other resistances in the circuit), $\frac{E}{R+\frac{r}{2}}$ will be the strength of the principal current when the extra wire is added; if now an additional resistance $= \frac{r}{2}$, that is to say a wire, whose resistance is equal to half that of the galvanometer wire, be added to the principal portion of the circuit, the intensity will be again $\frac{E}{R+\frac{r}{2}+\frac{r}{2}}$, and the force, acting on the galvanometer will be exactly half what it was at first."

We will further cite, among the numerous applications, which Wheatstone has made of the properties of derived currents, that, by means of which he succeeded in measuring currents of a considerable intensity by means of a very sensitive galvanometer, which would be impossible if the galvanometer was simply placed in the circuit of these currents. With regard to other applications, and to the details of the construction of the apparatus, we refer those who desire to know them, to Wheatstone's original Memoirs entitled "*An Account of several new Instruments and Processes for determining the Constants of a Voltaic Circuit.*"—*Phil. Trans.* Part II. 1843.

"When a galvanometer is employed to measure the force of a current, its wire is usually interposed in the circuit. But it is impossible, in this way, to make use of the same galvanometer to

measure the force of the current in circuits of different kinds. A galvanometer with numerous coils of thin wire adds a very considerable resistance to a circuit, in which the electro-motive force is great and the resistance small; while, on the other hand, a galvanometer with a short thick wire will give scarcely any indication in a circuit, in which the resistance is very great, though the electro-motive force may be considerable. Besides, a delicate galvanometer is incapable of indicating energetic forces.

"But, by the following simple means, the same delicate galvanometer may be employed to measure forces of every degree of energy, and in all kinds of circuits, without introducing any inconvenient resistance into them.

"If the current be caused to pass simultaneously through two paths, one being the wire of the galvanometer, and the other another wire connected with its two ends, the current will be divided in the inverse proportion to the resistances of the two paths. The action upon the needle of the galvanometer may hereby, by employing different wires to divert a portion of the current, be reduced to any degree. If the proportionate forces are known for the galvanometer without the reducing wire, they will remain equally proportionate, whatever the resistance of the latter may be; but measures made with the same instrument, with different reducing wires applied, will not be comparable unless the changed resistance of the galvanometer thus modified be taken into account.

"But strictly comparable measures may be obtained, if the precaution be taken of adding to the principal portion of the circuit, a resistance which will compensate for the diminution of resistance, occasioned by placing the reducing wire. Let g be the reduced length of the galvanometer wire, and $n\,g$ that of the reducing wire. The force of the current in the principal portion of the circuit will be to that in the galvanometer wire as $1 : \frac{n}{n+1}$. The resistance to be added to the principal portion of the circuit, in order to maintain the current the same as when no reducing wire is added, is $\frac{n\,g}{n+1}$.

"When the measures of energetic currents are required to be determined by means of a delicate galvanometer, it is sufficient to attach its two ends to two points of the conducting wire. The distance between these points must remain the same in all comparative experiments, but the absolute deviations of the needle

will be greater as these points are further from each other. In the case of the circuit of a powerful electro-magnetic engine, or of a volta-typing apparatus, the diminution of resistance occasioned by connecting the galvanometer wire in the manner above described is so trifling, that it would be useless to take it into account, and the compensation above alluded to is therefore unnecessary."—*Ibid.* pp. 322–3.

NOTE C. (pp. 153. and 217.)

Note relative to the Laws of the Discharges of Electric Batteries.

The following is the method whereby Riess has succeeded in establishing the law of the proportionality of the explosive distance of the discharge to the density of the electricity accumulated upon the conductor, whence the spark comes out; a law which he expresses by the formula $d = b \cdot \frac{q}{s}$; d expressing the distance, at which the discharge takes place, or the explosive distance; q, the absolute quantity of accumulated electricity; s, the surface of the conductor (the relation $\frac{q}{s}$ being thus the mean density of the electricity); and finally b being a constant. We have already seen that Riess' experiments, by means of the spark-micrometer, determine this constant b, and give a remarkable verification of the law,—such that, on setting out from the value found for b, which is 0·833, we may make use of the above formula in order to deduce from it q, when we know d and b. But it remains for us to know the method, that has been followed by Riess, in order to establish the law. This consists in causing the distance of the discs of a condenser to vary; and in measuring by means of the torsion-balance the density of the free electricity upon the inducing plate. Tables are thus constructed, in which the distances of the plates, and the corresponding densities are placed opposite to each other. In a second series of experiments, the distances of the discs were made to pass through the same values as in the former series; and by measuring the explosive distances by means of the spark-micrometer, new Tables were obtained, wherein the distances of the plates, and the corresponding explosive distances, were placed opposite to each other. Hence nothing further remains than to

prove that there exists approximately between the densities the same relations as between the explosive distances.

The condensing apparatus is composed of two discs of brass, supported vertically upon insulating feet, and of which one—the condenser—is so arranged as to slide along a graduated rule, the divisions of which indicate the respective distances of the two discs. To the outer surface of the collector is fixed normally a conducting wire, terminated by a ball; it is the electric density of this sphere, which serves as a measure to that of the plate; the determination of this density is then made with a small proof-ball, which is placed at 0° of the torsion-balance; the relation of the torsions gives the relation of the densities, which vary with the distance of the discs.* Riess takes for a unit the electric density of the collector for an infinite distance from the condenser; that is to say, when the latter is no longer acting.

Distances of the discs - - ∞	50	20	15	10	5	4	3	2
Density - - 1	0·897	0·683	0·595	0·492	0·335	0·186	0·135	0·173

This measure of the explosive distances was made by means of the spark-micrometer, the fixed ball of which communicates with the sphere of the collector, and its movable ball with the ground. The following is a Table, corresponding to the preceding one, and in which the unit of explosive distance is that which is found for an infinite distance of the discs; that is to say, for a distance at which they no longer have any influence over each other.

Distances of the discs ∞	50	20	10	5	2
Explosive distances - 1	0 914	0·687	0·451	0·272	0·105

We see, on comparing the two Tables, that the numerical results agree better in proportion as the distance of the discs is greater; which is doubtless due to the induction of the movable ball upon the fixed one; an induction, the energy of which increases very

* We must, in fact, mention, that the operation is commenced by charging the collecting disc, when it is beyond the influence of the condensing disc, with all the electricity that can be transmitted to it by the source with which it is in communication; the collector is then gradually brought near, so as constantly to diminish the quantity of free electricity, which must indeed become less in proportion as the discs are nearer to each other: the total quantity of electricity always remaining constant. It is this free quantity, whose density and explosive distance are compared.

rapidly when the two balls approximate. It is by means of a great number of experiments analogous to these, whose results are contained in the above Tables, that Riess arrived at the important law that *the explosive distance in a point of the collecting disc is proportional to the electric density in this point.*

NOTE D. (p. 230.)

Note relative to the Formula relating to the Electric Thermometer and to the Laws of Heating by Electric Discharges.

Riess has established the formula, which, in the electric thermometer, gives the temperature of the wire traversed by the discharge, or by the electric current, when the falling of the liquid has been determined in the thermometric tube. Let T be the temperature of the wire, that is required to be determined, at the moment when the current passes; the heating of the wire raises the temperature of the air of the globe, and causes it to pass from t to t'. Its elastic force consequently increases, and from p becomes p'; p' being determined from the relation $\frac{p'}{p} = \frac{1 + a\,t'}{1 + a\,t}$ or $p' - p = \frac{p\,t' - t}{\frac{1}{a} + t}$; in which a is the co-efficient of the dilatation of the air, and p, the barometric pressure observed at the moment of the experiment, which we will designate by b. Let θ be the number of divisions traversed by the liquid (the unit employed by Riess is the line); let ϕ be the angle of the graduated tube with the vertical; $\theta\ cos.\ \phi$ is the height of the column of liquid displaced by the elastic force of the air of the globe; and $\frac{\theta\ cos.\ \phi}{u}$ is the height of this column reduced into mercury; $\phi + \frac{\theta\ cos.\ \phi}{u}$ would therefore be the value of p', if no account was taken of the change of volume of the air; now, let K be the primitive volume of the air expressed in cubic lines, let d be the section of the tube, the relation of the two volumes occupied by the same mass of air will be

$$\left(\text{making } \frac{K}{d} = k\right), \frac{k + \theta}{k} \text{ or } 1 + \frac{\theta}{k}$$

We have therefore $p' = \left(b + \frac{\theta \cos.\phi}{u}\right) \cdot \left(1 + \frac{\theta}{k}\right)$ by substituting for p and p' their values in the first equation; and, by co-ordinating in respect to θ, we arrive at the following equation:

$$\theta^2 + \theta\left(\frac{b\,u}{\cos.\phi} + k\right) - \frac{k\,u\,b}{\cos.\phi} \cdot \frac{(t'-t)}{\frac{1}{a} + t} = 0;$$

which, on placing $\frac{u}{\cos.\phi} = e$, gives

$$\theta = \frac{k + e\,b}{2} \mp \frac{k + e\,b}{2} \sqrt{1 + \frac{4\,k\,e\,b}{\left(\left(\frac{1}{a} + t\right)\left(k + e\,b\right)\right)^2} \cdot (t' - t)}$$

The development of the expression, which is under the radical, when k is very great in respect to the other quantities that enter into it, which is the case here, gives an excessively convergent series, the first two terms of which are amply sufficient for all the values of $(t'-t)$, that may be presented in experiments. We have thus for θ the very simple expression

$$\theta = \frac{k\,b}{\left(\frac{1}{a} + t\right) \cdot \left(\frac{k}{e} + b\right)} \cdot (t'-t) \cdot (1)$$

We have now to express the elevation of the temperature of the wire in a function of the elevation of temperature of the air of the globe. And it is in this part of his calculation that Riess neglects the action of the glass envelope upon the air that it contains; but we have already said that this action may be entirely neglected; for the descending of the liquid takes place in a very short time, and the difference of temperatures of the envelope and of the air is always extremely feeble. Let then M be the mass of the wire, that traverses the globe; C its specific heat; m and c the same elements for the air. When equilibrium of temperatures is established, we have necessarily the following relation

$$(T - t)\ M\,C = (t' - t)\ m\,c; \text{ whence}$$

$$(T - t) = (t' - t)\frac{m\,c + M\,C}{M\,C}$$

Riess here for m substitutes $\frac{\mu\ b}{1 + a\ t}$, calling μ the mass of air, that would fill the same volume of the globe at the temperature of 0° (32° Fah.), and under the pressure of 1 line.

By thus making the value of t and of b enter into the expression of m he finally succeeds in being able to compare together the

experiments, in which these elements are no longer the same. We have therefore

$$T - t = (t' - t)\left(\frac{\mu b c}{M C (1 + a t)} + 1\right) \quad (2) \ .$$

On now eliminating $(t' - t)$ between the equations (1) and (2) we arrive at the following relation :

$$T - t = \theta \left\{ \left(\frac{1}{a} + t\right) \cdot \left(\frac{1}{e b} + \frac{1}{k}\right) \cdot \left(\frac{\mu b c}{M C (1 + a t)} + 1\right) \right\} \quad (3$$

According to which we see that the elevation of temperature of the wire is proportional to θ, provided that t and b are constant.

But it is moreover easy to find the expression of the errors that are committed in making use of the formula (3) in this case, in which t and b sensibly vary. Indeed, on differenting the equation (3) in respect to b, and in respect to t, we have :

$$d\theta = \frac{\frac{\mu c}{M C (1 + a t)} - \frac{k}{e b^2}}{\left(\frac{k}{e b} + 1\right) \cdot \left(\frac{\mu c b}{M C (1 + a t)} + 1\right)} \theta \, d b$$

$$d\theta = \frac{a \theta \, d t}{\frac{\mu b c}{M C} + (1 + a t)}$$

Expressions according to which it is easy to see that the inevitable error of experiment would greatly exceed these corrections.

Indeed, in the unfavourable case, in which a platinum wire of $0'''$ in diameter, and $5'''$ in length, might be placed in the globe, we should have: 1st, If the barometric height varied from 360 to $360 + d b$;

$$d\theta = 0{\cdot}000355 \, \theta \, d b$$

for a variation of temperature from 15° to $15° + d t$;

$$d\theta = 0{\cdot}0000095 \, \theta \, d t.$$

It is by means of the electric thermometers, of which we have been giving the formula, that Riess has established the different laws relative to the development of heat brought about by electric discharges through wires. We have put forth in the body of the work the principal of these laws; we shall not return to them, contenting ourselves with referring those of our readers, who might desire to have further details, to the Treatise on the Electricity of Friction by Riess—*Die Zehre von der Reibaugs Electricitat*, von P. S. Riess: Berlin, 1853.

NOTE E. (p. 375.)

Note relative to the Electrolytic Decomposition of Complex Compounds.

We shall here, by giving the summary of the numerous important experiments of MM. Daniell and Miller, complete the details on the electrolysis of secondary compounds, which we have not given, on account of their extent, in the body of the work. We refer, for the description of the experiments themselves, to the Memoir of these two English philosophers, entitled, *On the Electrolysis of secondary Compounds, inserted in the Philosophical Transactions of the Royal Society of London*, Part I. for 1844.

We shall confine ourselves to remarking that the experiments were made by means of an apparatus with three cells separated by two diaphragms of bladder, and so arranged that the gases might be collected, which were liberated in the two extreme cells at the surface of the two platinum electrodes, that plunged into them. A voltameter with acidulated water was always in the circuit, in order to measure the equivalent of electric force. The three cells were filled either with the same liquid or with different liquids. The experiments were made upon the different phosphates, arseniates, arsenites, sulphates, sulphites and hyposulphites; upon the various ferro-cyanurets of potassium, upon the double salts of copper and potash, magnesia and potash, &c. The following are, word for word, the conclusions, that the authors have deduced from their researches.

"In every instance the definite action of the electric current is maintained; and its passage through a compound liquid conductor is always marked by the disengagement at the platinode of hydrogen or the metallic element, or else of a group of substances, like ammonium, constituting an equivalent compound; and the simultaneous disengagement at the zincode of the non-metallic element, or a group of substances of iso-electric powers. Of such electrolytes it may be convenient to distinguish the following classes: —

"1st. An electrolyte may consist of *simple ions*, and then must be constituted of a single equivalent of a metal (or H) for its cation, and a single equivalent of a non-metallic element for its anion; as K, I; AG, CL; &c.; they may be termed simple electrolytes.

"2nd. An electrolyte may consist of a *compound cation*, a single

equivalent of which must take the place of a metal; and a single equivalent of a *simple non-metallic anion*, as NH_4, *cl.* Organic alkalies probably form compound cations of this nature, and when their salts are electrolysed, hydrogen is always disengaged with them at the platinode, as with ammonia: these and the following we may call *complex electrolytes.*

"3rd. An electrolyte may consist of a *compound anion*, a single equivalent of which would take the place of the simple non-metallic anion, with a single equivalent of a *simple cation*, a metal (or H), as H, NC_2; K, SO_4; NA, NO_6.

"4th. An electrolyte may consist of a single equivalent of a *compound cation*, and a single equivalent of a *compound anion*, as NH_4, SO_4.

"These four cases may be included in the term *Monobasic Electrolytes*, as a single equivalent of force (measured by the voltameter) would electrolyse single equivalents of the electrolytes.

"5th. An electrolyte may also consist of *two or more equivalents of a metallic cation* or (H), or of *single equivalents of two or more metallic cations* or (H); when the *anion* must consist of a single equivalent of a compound ion, as (K_2 FE CY_3). This compound ion, in the case of the oxysalt, contains the so-called anhydrous acid in combination with as many equivalents of oxygen as there are of metallic cations (or H) in the compounds, as (NA_3, P_2, O_5, O_3). In this case as many equivalents of force will be required for the electrolysis of one equivalent of the electrolyte as there are equivalents of metal (or H) in the cation. They may be denominated *Polybasic Electrolytes.*

"In these compound anions and cations, it would appear that the oxygen which travels with the acid group, and the hydrogen which is evolved with the alkaline group, must be connected with the other elements whilst under the influence of the current in a manner differing from that in which the latter are combined together; for we have found that in most cases this connection is immediately dissolved upon their escape from the electric influence, whilst in some others their apparent permanent combination is only the effect of secondary action, where the oxygen is capable of forming a chemical compound of a higher degree of oxygenation and, like other secondary actions of a similar nature, is variable in its amount.

"The disengagement of the cation and anion of an electrolyte in equivalent proportions is not always effected, as is commonly represented, by their simultaneous transfer in opposite directions

to their respective electrodes, in the exact proportion of half an equivalent of each; but is sometimes brought about by the transfer of a whole equivalent of the anion to the zincode, whereby a whole equivalent of the cation is left uncombined at the platinode; or by transfer of unequivalent portions of each in opposite directions, making however together a whole equivalent of matter transferred to one electrode or the other; or speaking more correctly, *by the transfer of a quantity of matter capable of exerting one equivalent of chemical force*, so that when the anion *transferred* to the zincode exceeds half an equivalent, the cation transferred to the platinode is in an equal proportion less than half an equivalent, and *vice versâ*; the anion and cation *set free* being always in equivalent proportions. We have, however, in no case observed the transfer of a whole equivalent of the cation to the exclusion of the anion."

MM. Daniell and Miller have seen in the results of their experiments a serious objection against the molecular theories of electrolysis, such as they were formularised by Grotthus and by Daniell himself, and such as we have ourselves explained them. We think, on the contrary, that all the anomalies or apparent exceptions to these theories, that may be presented by the facts, observed by the English philosophers, are very well explained, if we have regard to the very just observation of M. D'Almeida that, in the electrolysis of solutions, account must be taken of the conducting powers of the different parts of the mixture that forms the solution, in such sort that it is the most conducteous that are electrolysed; and that the substances, which show themselves at the electrodes, are often secondary products. (For further details on the researches of M. D'Almeida, see his original memoirs, *Arch. des Sc. Phys.* (*Bibl. Univ.*) t. xxix. p. 5., the principal results of which we have given in the body of the work, p. 384. and following pages.)

NOTE F. (p. 787.)

Note relative to M. Poggendorff's Method for the Determination of the Electro-motive Force of a non-constant Current.

M. Poggendorff's method differs essentially from all others, in that it measures, not the current itself, but the tendency to the formation of the current: now, as in currents of non-constant force, it is the action of the current itself, which gives rise to the disturbing

causes that destroy its constancy, it is evident that these causes cease to exist from the moment that the current does not enter into activity. The question, then, is to compensate the current of non-constant force by a current of constant force, and to deduce from the nature of the latter, the electro-motive forces of the former; we cannot, it is true, create hydro-electric currents, whose electro-motive forces have determinate values; but we are able, when once we have a like force of a constant nature, to determine any aliquot part of it, and to employ it in this compensation.

Let A be the pair of constant force; B, the pair of non-constant force; the two positive electrodes are joined together at the point P, the two negative electrodes at the point N; and these two points of junction are united by the conductor O; let us consider the following quantities: —

I N	O	A	B	
Electro-motive force	K	K′	K″	
Resistance	r	r'	r''	
When A alone acts	i	i'	i''	Intensities of the currents.
„ B „ „	i_2	i'_2	i''_2	
„ A and B act	I	I'	I''	

According to the principle that the current produced by each pair are added, or are deducted, according to their direction, without interfering with each other, we obtain the following equations.

$$\left.\begin{aligned} I &= i + i \\ I' &= i' - i'_2 \\ I'' &= i''_2 - i'' \end{aligned}\right\} \quad (1.)$$

The laws of derived currents give the two following relations, supposing that the pair A is alone in action; $i' = i + i''$ and $i\ r = i''\ r'' = h'$; h' designating any one of these two products. From these two equations we deduce $h' = i' \left(\frac{1}{\frac{1}{r} + \frac{1}{r''}} \right)$; in which $\frac{i}{r} + \frac{i}{r''}$ is the resistance of the conducting system, formed by O, and the pair B; h' therefore represents the electro-motive force in that system, whence the relative results $i'\ r' + h' = K'$, which expresses that the electro-motive force of the circuit is equal to the sum of the electro-motive force of the different longitudinal parts of this circuit.

From these three relations, we deduce the values of i, i', and

i'', and, for the sake of abbreviation, making $s = \frac{i}{r} + \frac{i}{r''}$, $i = \frac{K'}{r' s r}$,

$$i' = \frac{K'(r' s - i)}{r' s r} = \frac{K'}{r' s r''}.$$

We find, in the same manner, the value of i_2, i'_2, and i''_2, supposing that the pair B is alone in action.

The equations (1) now become

$$1 = \frac{i}{s r}\left(\frac{K'}{r'} + \frac{K''}{r''}\right)$$

$$1' = \frac{i}{s r'}\left(\frac{K'(s r' - i)}{r'} - \frac{K''}{r''}\right)$$

$$1'' = \frac{i}{s r''}\left(\frac{K''(s r'' - i)}{r''} - \frac{K'}{r'}\right).$$

Let us now suppose that the intensity of the current in the pair B is null. $1'' = 0$; which gives $K'' = \frac{r}{r + r'} K'(1)$; substituting this value of K'' in the other two equations, we find $1 = 1' = \frac{K'}{r + r'}$, and this relation, compared with the preceding, gives $K'' = r\,1$ (2).

Thus, by means of a galvanometer, placed in the circuit of the pair B, we prove that, at each moment, we have $1'' = 0$; and we will make use of the relations (1) and (2) in order to determine K'', which is the electro-motive force of these two non-constant pairs. M. Poggendorff, on applying each of these two formulæ, has been led to the two following processes.

First Process.—Let B be an ordinary pair, zinc and copper with a single liquid; we chose for A a pair of constant and considerable force, for example, Grove's pair. We cause the zinc plates of both pairs to communicate by means of a conducting wire *a*, and the zinc of B to communicate with the platinum of A by means of the wire *b*; finally, this same platinum plate is joined by the wire *c*, with the copper of the other pair; the wire *c* includes a very sensitive galvanometer.

In this state of things the wire *a* and the liquids at A give the resistance r; the wire *b*, the resistance r'; and, when these two resistances have a certain relation with each other, there is no current in the wire *c*, nor, consequently, in the pair B; we arrive at this result, by modifying little by little the length of the wire *b*, until the needle of the galvanometer no longer deviates from 0°;

and, taking care, after each approximation, to leave the circuit B open for a certain time, in order to cause all force of polarisation to disappear. When once equilibrium is well established, M. Poggendorff measures the resistance of b with the greatest accuracy; the elements of the Grove's pair have been determined by the ordinary processes; and K″ is found by the formula $K'' = \frac{r}{r + r'} K'$. M. Poggendorff has obtained a verification of this method by measuring the electro-motive force of a pair of Daniell's already obtained by Ohm's process.

Ohm's method $\begin{cases} \text{Grove} & K' = 25{\cdot}886 \\ \text{Daniell} & K'' = 15{\cdot}435 \end{cases} \quad \frac{K'}{K''} = 1{\cdot}677.$

Method of compensation $\begin{cases} r' = 35{\cdot}03 \\ r = 52{\cdot}68 \end{cases} \quad \frac{K'}{K''} = 1{\cdot}668.$

Second Process.— The two pairs are arranged precisely in the same mechanical manner; only it is necessary to introduce into the wire b a galvanometer; when we have proved that the current in the wire c is annulled, we measure the resistance of b, and the intensity of the current, that is found in it; if we make use of a sine-compass, calling a the angle of deviation, we have for K″ : $K'' = r \sin a$.

This process has this advantage over the former, a containing implicitly K′ and r'; even when these elements come to vary in the interval of the successive experiments, they always enter into the calculation with their initial values, since the measure of a is made at each experiment; in the first process, it is necessary in this case to determine from time to time the electro-motive force, and the resistance of the non-constant pair, which is always a very long operation. M. Poggendorff, in comparing his two processes, has shown that they agree within a great degree of accuracy.

NOTE G. (p. 821.)

Note Relative to the Mathematical Theory of the Pile.

We have established in the First Chapter of our Fourth Part, as one of the general laws of the propagation of electricity, that the intensity of a current in a closed circuit is proportional to the algebraic sum of the electro-motive forces, that are developed by any cause in the different parts of this circuit (a force being taken with its signs). This law, which Ohm was the first to put

forth with this mathematical rigour, in deducing it from *à priori* considerations, has been experimentaliy verified both by Fechner and by Pouillet for hydro-electric and thermo-electric circuits. But, in its generality, the law is applicable to every species of circuits, as well as to those, that we have been pointing out; and in particular to the circuits in which the electro-motive force is developed by the inductive action, that is exerted upon them in one of their portions of greater or less length by the approach of a magnet or of a closed electric circuit. It is, therefore, independent of the nature of the electro-motive force; and, consequently, also, of every species of hypothesis, that may be made as to this nature. We may have a closed circuit without there being any current that is circulating in it; such is the case in a thermo-electric circuit, all the parts of which are at the same temperature; —of a circuit intended for induction, before it has been submitted to the inducing action; these circuits possess a force of resistance, which they always oppose equally to every current that may traverse them, whether this current is derived, either from an electro-motive force, that is exterior to them, or from an electro-motive force, that is excited in one or in several of their parts, for example, on heating the odd points of contact of the heterogeneous portions of the circuit, or on determining upon a certain part of this circuit an inductive action. We find, in Pouillet's *Traité de Physique**, the detailed exposition of the experiment, and very simple calculations by means of which this learned philosopher has succeeded in establishing the general formula of the intensity of a pile composed of any number of pairs, whose individual intensity and resistance are given. We have, moreover, already demonstrated the accuracy of this formula on many occasions; we may, therefore, employ it either to solve the question of knowing how we may discover or obtain the maximum intensity of a pile. In order to arrive at the solution, we follow the method pointed out by Poggendorff, and the results of what we have already made known in the body of this work (p. 821. and following pages).

We have $i = \frac{e}{r+l}$, calling e the electro-motive force of a pair, r the resistance of this pair (*essential* resistance and constant of the circuit) l, the accessory and variable resistance exterior to the pair. If we designate by m, the maximum of intensity of the

* *Eléments de Physique et de Météorologie*, par M. Pouillet. Sixth edition; Paris, 1853, vol. i. p. 631. and following pages.

current, we have $m=\frac{e}{r}$. We may approach this maximum, which takes place when $l=0$, either by diminishing as much as possible the resistance l, (by employing a very good conductor for closing the circuit) or by rendering n as great as possible, namely, by increasing, as much as possible, the number of pairs of which the pile is formed. In this manner l disappears before $n\,r$, in the general expression $\frac{n\,e}{n\,r+l}$ and we have $\mathrm{I}=\frac{e}{r}=m$.

If we have a second circuit, whose elements, corresponding to those of the former, are e', r', l' and i' we have, in a general manner, the following expression for the relation of the two circuits:—

$$\frac{i}{i'}=\frac{e}{e'}\cdot\frac{r'+l'}{r+l}$$

If we suppose $l=l'$, let us then make $l=0$; then, $l=\frac{1}{0}$; we have, in the former case, $\frac{i}{i'}=\frac{e}{e'}\cdot\frac{r'}{r}$, and in the latter $\frac{i}{i'}=\frac{e}{e'}$. The first limit is the relation of the maximum current, since $m=\frac{e}{r}$ and $m'=\frac{e'}{r'}$. The second limit is the relation of the electro-motive force. These two limits are themselves in respect to each other inversely as the essential resistances of the two circuits.

The relation of the maximum currents enables us to solve the question of knowing how we may obtain the maximum of useful effect in various cases. We shall confine ourselves here to the most interesting limit of these cases,—that of which we have given the solution in the body of the work, without giving its demonstration. The following is this case:—Two metallic surfaces (amalgamated zinc and platinum, for example) being given, how many pairs must be made of them in order to obtain a pile, that shall produce the maximum of effect in a mechanical or calorific voltameter, placed in its circuit? The distance that is to exist between the plates of the pairs, and the liquid or liquids, that are to be employed for charging the pile, are also given.

The chemical effect of the current being proportional to its intensity, and its calorific effect to the square of its intensity, the useful effect will be in this case the greatest possible when the intensity of the current shall be a maximum. Let, therefore, l be

the resistance of the voltameter, as well chemical as calorific; which may always be represented by that of a wire of a certain nature and of given dimensions; λ, the resistance of the liquid, that enters into the formation of this pile, for a unit of section and for a length equal to the distance between the plates of each pair, σ the size of the surface to be given to each plate, and s the size of one of the two given metal surfaces, which are equal to each other. In the general expression $\mathrm{I}=\frac{n\,e}{n\,r+l'}$, we have $r=\frac{\lambda}{\sigma}$, since the resistance of the pair must be directly proportional to that of the liquid, and inversely to its section. We have, on the other hand, $n=\frac{s}{\sigma}$, which gives $r=\frac{n\,\lambda}{s}$. Substituting for r its value in the expression of I, we have, $\mathrm{I}=\frac{n\,e\,s}{n^2\,\lambda+s\,l}$; so that the intensity of the current is expressed in a function of the only variable n.

We have, therefore, nothing more than to decide what is the value of n, that will render this expression a maximum, and for this purpose, we must make its derived value equal to 0; which gives $e\,s\,(n^2\lambda+s\,l)-2n^2\,\lambda\,e\,s=0$; whence we deduce

$$n^2=\frac{s\,l}{\lambda}\text{ or }l=\frac{n^2\,\lambda}{s}=n\,r;$$

since $r=\frac{n\,\lambda}{s}$.

Thus, as we have stated in the text (p. 821.), the intensity of the current, that produces the maximum of effect, takes place, when the number of the pairs is such that the interior resistance of the pile is equal to that, which the current must surmount exteriorly in one or other of the two voltameters. We have consequently for the value of the maximum of useful effect

$$\mathrm{I}=\frac{n\,e}{n\,r+n\,r}=\frac{e}{2\,r.}$$

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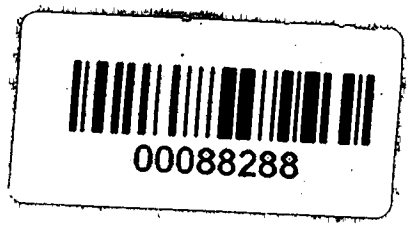
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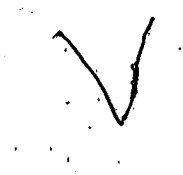

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